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CONTENTS

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RED RIVER OF THE NORTH BASIN FLOOD, APRIL-JUNE 1950

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ABSTRACT

One of the worst floods of record in the valley of the Red River of the North occurred during the spring of 1950. In this report on the flood, the general topographical and climatological characteristics of the basin are described, the meteorological conditions contributing to the flood are discussed, and data on the flood stages and duration are presented. Comparative data for other floods in the valley also are presented and the worst of these, the flood of 1897, is discussed.

CONTENTS

INTRODUCTION

Flooding in the Red River Valley of the North during the spring of 1950 was one of the worst floods of record in the valley with damages estimated at 33 million dollars. The crests during April were the highest since 1897 at Grand Forks, N. Dak., and the highest on record at Pembina, N. Dak. The crests during May from below Grand Forks, N. Dak., to the Canadian border were generally the highest in the past 100 years.

Floods in the Red River of the North Basin occur primarily during the spring season (April and May) and are caused chiefly by melting snow. Ice conditions, particularly on the northward flowing streams, increase flood crests and occasionally cause extremely high flood stages due to ice jams. Early freeze-up in the fall before snow occurs is also a contributing factor in producing flood conditions in the spring. Major rain storms of sufficient magnitude to cause more than local flooding are extremely rare. Considerably higher crests result along the tributaries and the main stem of the river if the snow melt is accompanied by a period of prolonged heavy rains. In the lower portion of a large drainage system extreme floods depend upon the relative times of occurrence of high water in the separate portions of contributory sub-areas of the system. If the floods from the different tributaries meet simultaneously in the main stream, an extreme flood results; but if they arrive consecutively, the major part of the water from one tributary may have passed by before that from the next tributary arrives and the same total quantity of water being distributed through a longer time causes no unusual heights.

The purpose of this paper is to describe how the contributing factors combined to produce the flood of April–June 1950. First, as a background for the discussion of these factors, of the resulting flood, and of previous floods in the valley, the general topography and climatology of the basin are described.

DESCRIPTION OF BASIN

The Red River of the North rises in the lake region of west-central Minnesota, not far from the headwaters of the Mississippi River. (See fig. 1.) It is formed by the confluence of the Ottertail and Bois de Sioux Rivers and flows 400 miles in a northerly direction between the states of Minnesota and North Dakota to the interna-

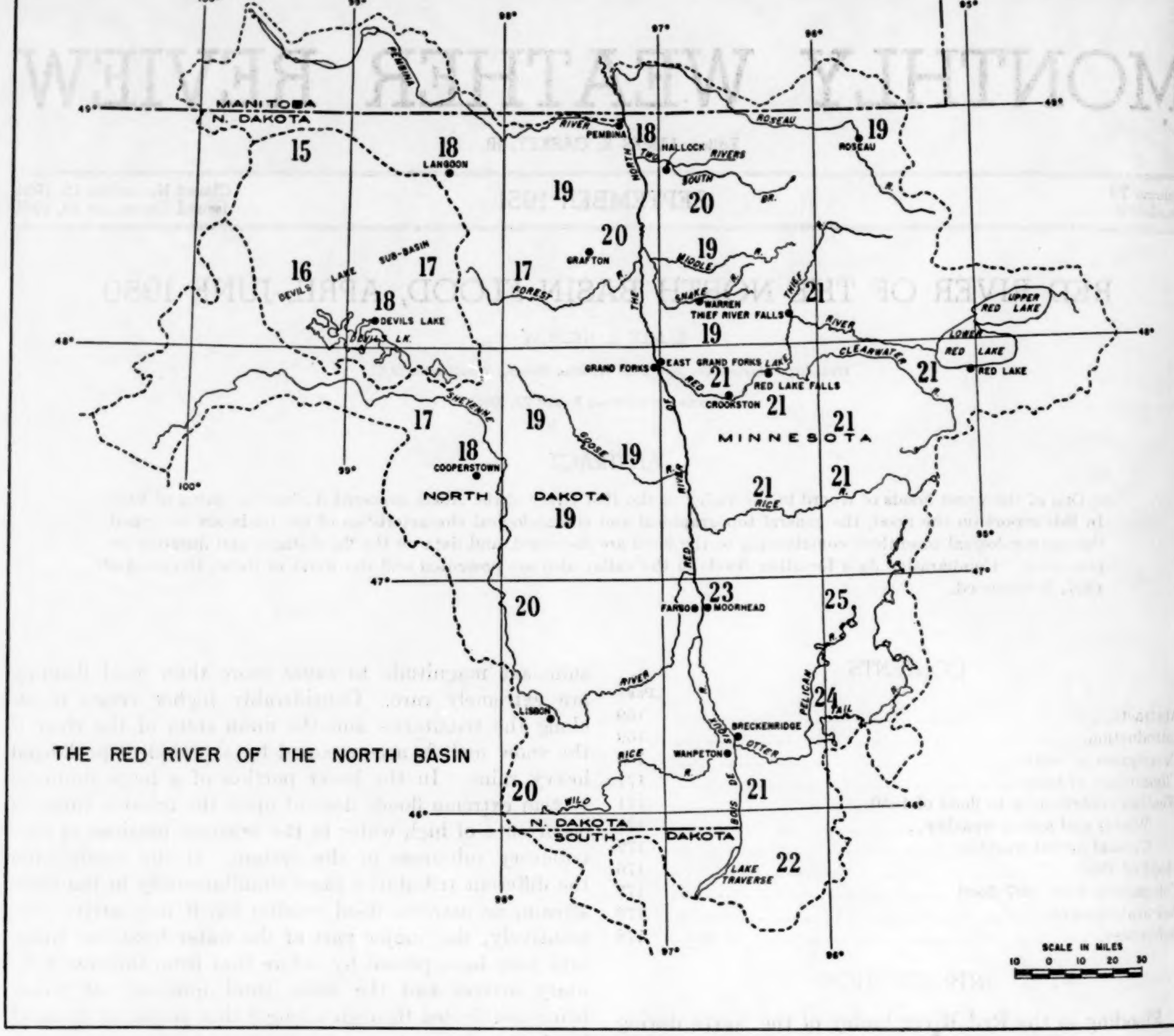

FIGURE 1.—Map showing principal streams in the basin of the Red River of the North. The plotted numbers are average annual precipitation (inches).

tional boundary. In Canada it flows generally northeastward about 155 miles into Lake Winnipeg which empties into the Hudson Bay by means of the Nelson River. The slope of the river varies from about 1.3 feet per mile near the source to 0.2 foot per mile near the Canadian boundary and averages about 0.5 foot per mile. In Canada the fall averages about 5 feet per mile. It is navigable along the greater portion of its course.

Several tributaries flow into the Red River of the North from North Dakota and Minnesota. The most important of these are the Sheyenne and the Pembina in North Dakota, the latter of which rises in the province of Manitoba, Canada.

The Red River of the North at the international boundary drains an area of about 40,200 square miles. Of this area, 21,000 square miles are in North Dakota, 16,400 in Minnesota, 800 in South Dakota, and 2,000 in Canada. The greater part of this Canadian area is drained southeastward into the United States by the Pembina River which joins the Red River of the North south of the Canadian border. Included in the total drainage area are 3,940 square miles comprising the closed Devils Lake subbasin in North Dakota.

The main river valley is very flat and varies in width from about 50 miles in the southern half to about 150 miles in the middle of the basin. The greater portion of

the basin has been submerged twice beneath the sea and was covered with an extensive glacial drift which left an immense lake called Lake Agassiz that had an outlet to the Mississippi River. The Lakes of Manitoba are the remains of this vast lake. Streams within the valley have flat slopes and channel capacities which are generally inadequate to carry flood flows. An extensive system of drainage ditches has been constructed in North Dakota and Minnesota to assist nature in carrying away the water.

CLIMATOLOGY OF BASIN

The Red River of the North Basin lies in a belt of prevailing westerly winds where the major rainfall occurs during the late spring and summer, with the greatest amount occurring in June. Approximately 60 percent of the total annual precipitation shown in figure 1 occurs during the growing season which has an average length of 100 to 140 days. Much of the summer precipitation, which frequently is associated with thunderstorms, is due to the forced lifting of warm moist air from the Gulf of Mexico over a wedge of cooler polar air. The winter months, December through February, are normally the driest in the year; approximately 15 percent of the total annual precipitation occurs during this period in the form of snow and accumulates to considerable depths in the valleys and wooded areas. The average annual precipitation varies from about 24 inches in the headwaters to about 17 inches in the north part (fig. 1).

The mean annual temperature of the Red River of the North Basin varies from about 43° F. in the southern portion to 36° F. in the northern portion. Temperature extremes of 118° and −54° have been recorded.

The total annual runoff in this part of the United States is very small, averaging about 3 to 4 inches per year from the Minnesota side of the Red River drainage and less than 1 inch from the Dakota side.

WEATHER CONTRIBUTING TO FLOOD OF 1950

WINTER AND SPRING WEATHER

The weather conditions during the winter and spring of 1950 in the Red River of the North Valley were favorable for the development of severe flooding in several respects. The over-all combination of conditions permitted the heavy accumulation of snowfall during the winter and late melting in conjunction with heavy precipitation in the spring. Early freeze-up in the fall before snow occurs is often a contributing factor to produce flood conditions in the spring but during the fall of 1949 the freeze-up was not early and the snow that fell during November 1949 melted by the end of the month. The cold weather in December, however, caused deep frost penetration in the ground before new snow occurred so the effect was similar to an early freeze-up. The winter and spring months were extremely cold, averaging several degrees below normal as shown in figure 2. March 1950

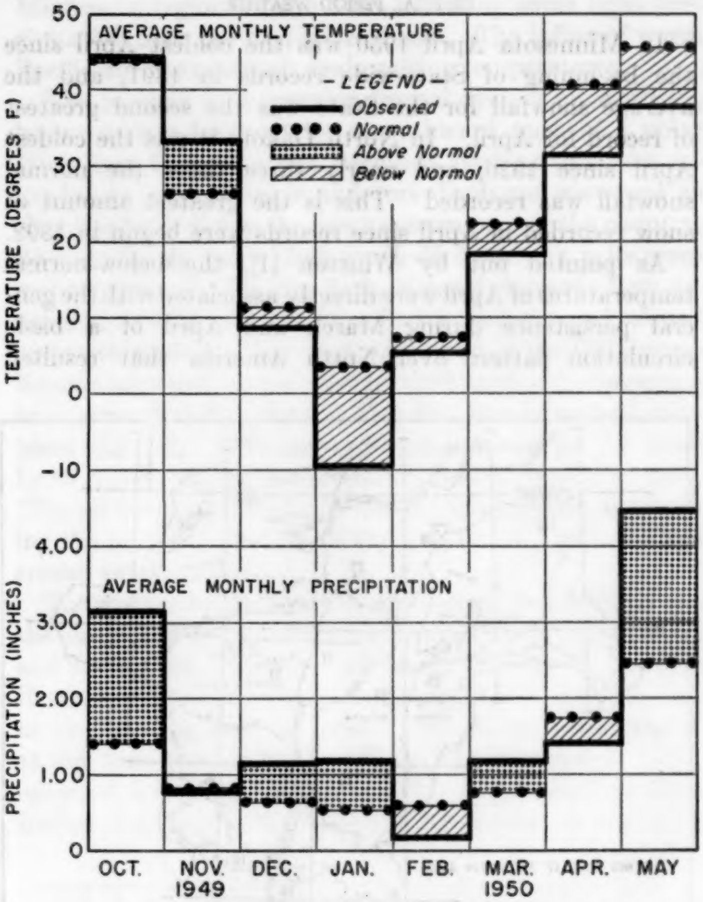

FIGURE 2.—Average monthly temperatures and average monthly total precipitation over the Red River of the North Basin from October 1949 through May 1950.

was the fourth consecutive month with below-normal temperature in North Dakota. Precipitation averaged considerably above normal during December 1949, January, March, and May 1950, with unusually heavy amounts in January and March (fig. 2). Although precipitation averaged below normal during February, the temperatures were abnormally low so there was little decrease in the heavy snow cover that was on the ground on February 1, 1950. A snow survey by the U. S. Army Engineers from February 12–18 showed the water equivalent of the snow cover in the upper portion of the basin during that period to be less than an inch, and in the northern portion from 2 to 3 inches. Warm weather during the first 6 days of March melted much of the snow cover over the south and central portions of the basin. Severe weather with abnormally cold temperatures occurred during the remainder of March. The severe weather was accompanied by additional snow in northeastern North Dakota and northwestern Minnesota. Figures 3, 4, and 5 show the amount of snow on the ground on February 1, March 1, and April 1, 1950. Figures 6 and 7 show isolines of percentage of normal precipitation over the Red River of the North Basin from October 1, 1949, to March 31, 1950, and from April 1, 1950, to May 31, 1950.

CRITICAL PERIOD WEATHER

In Minnesota April 1950 was the coldest April since the beginning of State-wide records in 1891, and the average snowfall for the State was the second greatest of record for April. In North Dakota it was the coldest April since 1920, and nearly three times the normal snowfall was recorded This is the greatest amount of snow recorded in April since records were begun in 1892.

As pointed out by Winston [1], the below-normal temperatures of April were directly associated with the general persistence during March and April of a basic circulation pattern over North America that resulted in repeated outbreaks of cold Canadian polar air into central and eastern United States. Winston further pointed out that the above-normal snowfall in the Dakotas was caused primarily by Pacific maritime air overrunning the cold polar domes covering the area. It is of interest to examine some of the day-to-day weather developments associated with this general circulation pattern, for they seem to indicate that some important contributions to the precipitation also were made by occasional influxes of moist Gulf air overrunning the polar domes.

As April 1950 opened, the valley of the Red River of the North was dominated by a polar High centered over

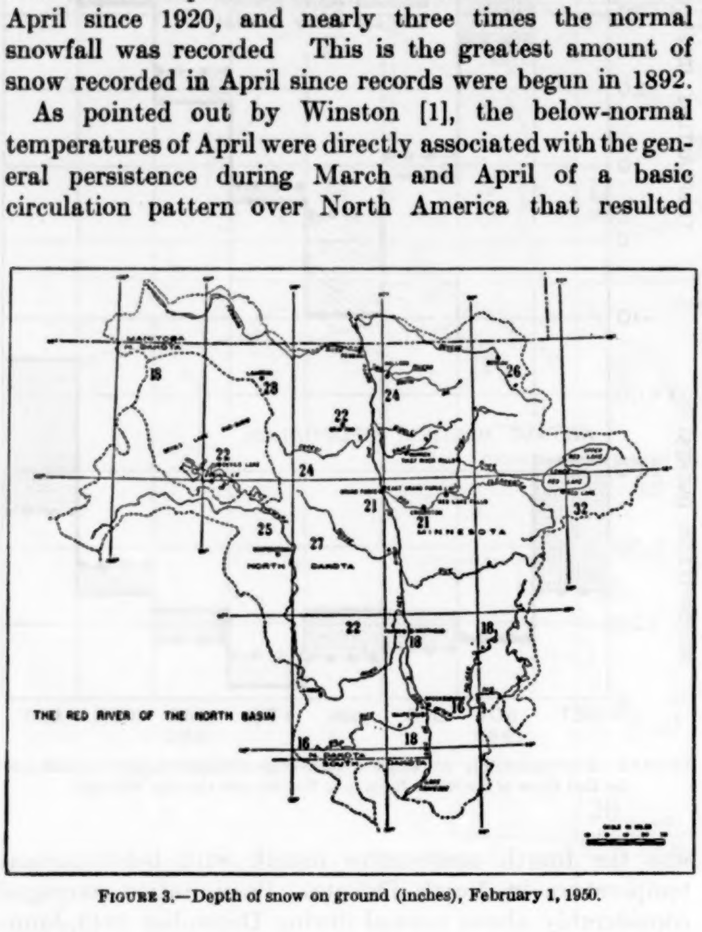

FIGURE 3.—Depth of snow on ground (inches), February 1, 1950.

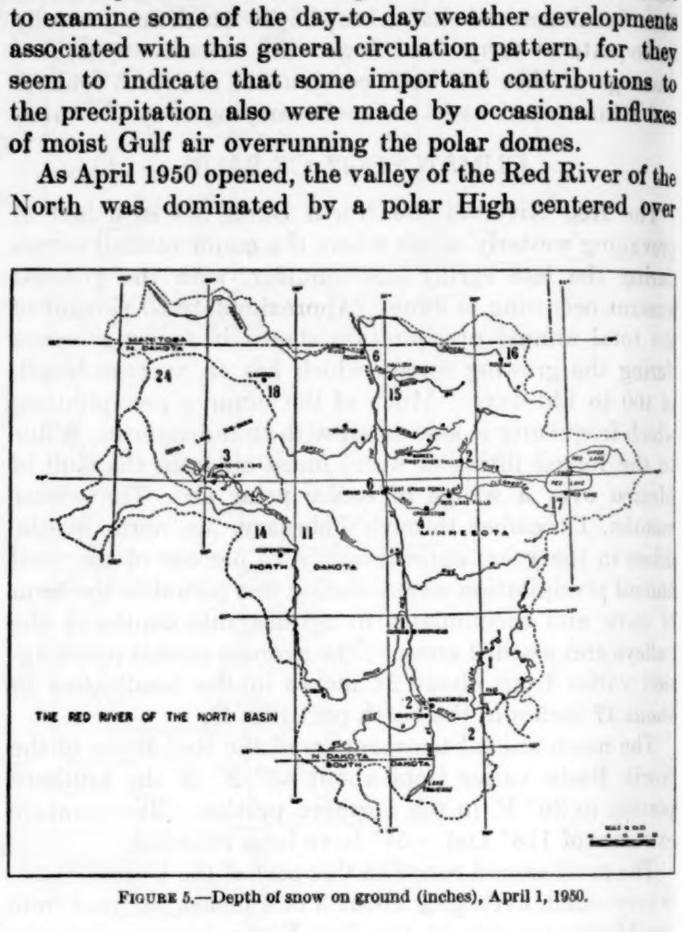

FIGURE 5.—Depth of snow on ground (inches), April 1, 1950.

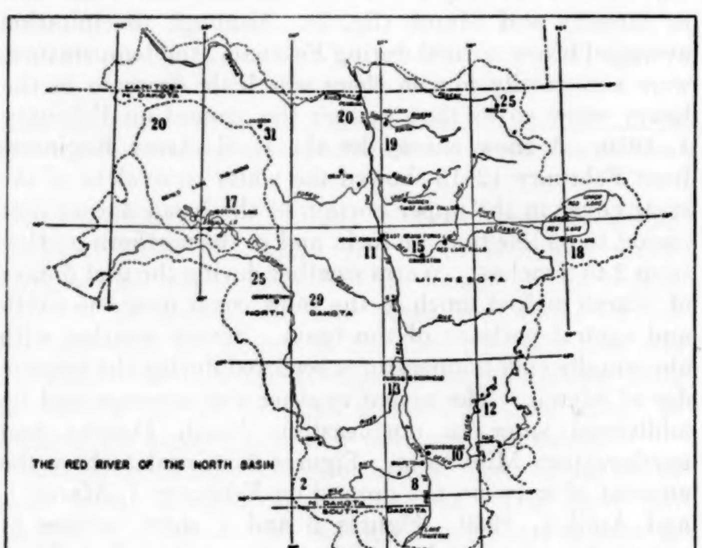

FIGURE 4.—Depth of snow on ground (inches), March 1, 1950.

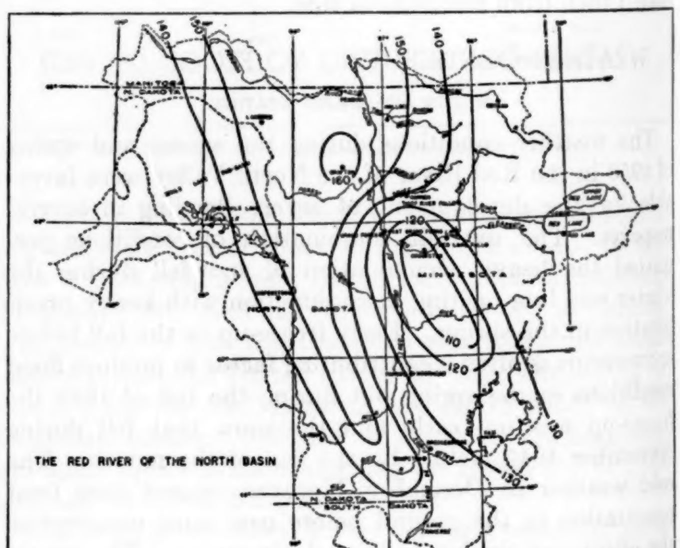

FIGURE 6.—Isolines of percentage of normal precipitation from October 1, 1949, to March 31, 1950.

western South Dakota. A deepening cyclonic system, however, was moving in on the west coast, just north of the Canadian border. The system moved rapidly east-southeastward, producing precipitation (primarily in the form of snow) over the Red River Basin, and causing a dip in temperatures (fig. 8). As the Low moved off east of the Basin, it was replaced by a polar High which, by afternoon of April 4, dominated the circulation of the United States from the west coast to the Mississippi.

A mass of polar air, building up in northwestern Canada at this time, moved slowly east-southeastward in the next 24 hours. By afternoon of the 7th the forward edge of the polar air mass had swept past the Red River Basin. Although the center of the High remained in Canada, the strong circulation around it poured cold air into North Dakota and Minnesota and sent temperatures plunging (fig. 8).

The High progressed eastward and was centered east of Hudson Bay on the 9th. At this time a front, extending from a Low in southern Wyoming, stretched eastward marking the southern boundary of the polar air mass. North of the front a huge area of precipitation from Ohio to the Dakotas was created as warm moist air from the Gulf of Mexico moved northward and was lifted over the cold air mass. Precipitation in the form of freezing rain and snow continued in most of the Red River area through the 11th when the Low was finally replaced by a wedge of high pressure.

The cold air of the High dominated the Red River area through April 14. In the following 2 days, two weak frontal systems from the Pacific crossed the Basin area bringing in mild Pacific air. Skies cleared and temperatures rose sharply (fig. 8). Still another Pacific system, stronger and slower moving, crossed the North Dakota-Minnesota region on the 17th, releasing some light precipitation over the Red River Basin. The influx of warm Pacific air was renewed, again raising temperatures.

The passage of a complex frontal system on April 22, however, was followed by a southward push of a polar High from Canada. The Bermuda High at this time extended to great heights and was displaced westward so that it intruded over the southeastern part of the country. As a result, the polar High was halted midway in its progress southward. On the 24th, a small dynamic Low developed in the cold air over North Dakota and moved eastward while another Low developed in the Oklahoma-Kansas area and moved slowly northeastward, deepening as it went (fig. 9). By the 25th the two Lows had combined (fig. 10). The strong circulation created by these Lows pulled warm, moist air northward from the Gulf. This air was then lifted over the denser polar air dominating the northeastern half of the country and caused widespread precipitation.

The Bermuda High slowly gave way on the 25th, and the deep Low pulled polar air down over North Dakota and Minnesota (fig. 10). At many stations in the Red River area maximum temperatures for the 25–27th were at the freezing level or lower. Minimum temperatures at this time were as low as 17° F. Devils Lake, N. Dak., reported 6.5 inches of snow on the 24th, and Red Lake Indian Agency, Minn., reported 6.9 inches on the 25th.

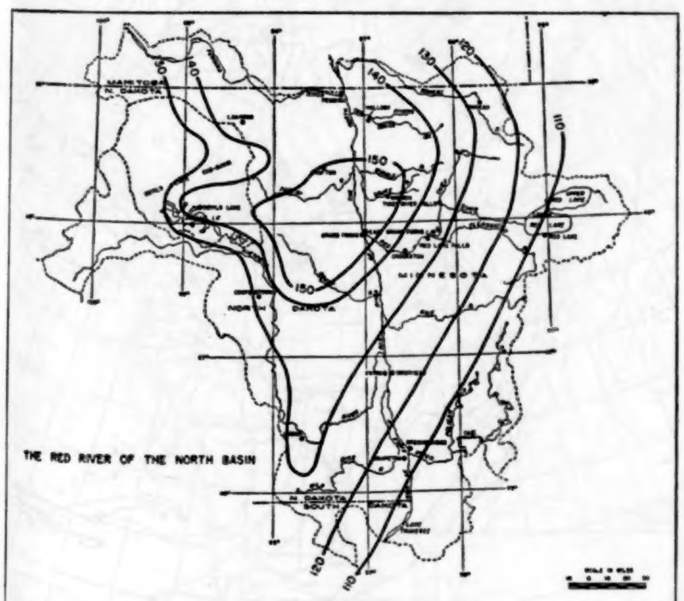

FIGURE 7.—Isolines of percentage of normal precipitation from April 1, 1950, to May 31, 1950.

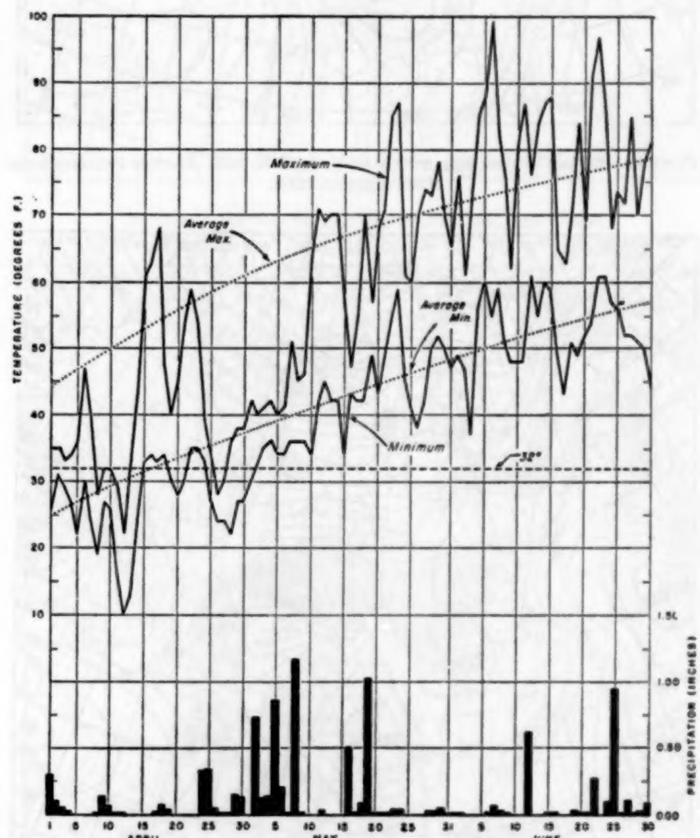

FIGURE 8.—Precipitation and temperature, April to June 1950, Fargo, North Dakota.

Pierce and Norton [2] have given a detailed discussion of these critical meteorological conditions of April 24–26.

As the Low finally moved off to eastern Canada and filled slowly, a new polar High descended over most of the eastern two-thirds of the country (fig. 11). Early on the 29th, however, the Bermuda High began to reassert itself. The southward progress of the polar air was halted and the warm air, moving northward, was lifted over the cold air mass. Precipitation fell over the Red River Basin on the 29th and 30th as a result.

May weather in North Dakota was a continuation of one of the most marked seasons-in-reverse ever experienced, while in Minnesota the spring months (March, April, and May) were the coolest in 60 years of record. Snowfall in both North Dakota and Minnesota established new records. In Minnesota the snowfall was the greatest recorded in May since 1924; in North Dakota the snowfall was twice the previous all-time high set in 1905. Precipitation in both States was above normal.

The main features of the general circulation in May to which Aubert [3] attributed the anomalous precipitation were a mean trough and center of negative 700-mb. height anomaly over the Dakotas. Again, however, a more detailed picture of the critical weather conditions is given by the day-to-day developments. As May opened, a polar High dominated the Red River Valley. Early on the 2d, however, the southerly winds of an approaching frontal system lifted warm, moist air over the cold dome, releasing heavy precipitation. Petersburg and Sharon, N. Dak., each received 8 inches of snow, and Thief River Falls, Minn., reported 6 inches. Trail, Minn., recorded 3.05 inches of precipitation on the 2d.

The frontal system had not yet passed on the morning of May 3, when another Low began to develop and deepen in eastern Utah. The Bermuda High again pushed its nose over the Southeast, retarding the southward push of the polar air mass. Precipitation started again on the 4th, and continued through the 6th as the circulation intensified with the rapid deepening of the Low. Just as the Low appeared to be moving out of the range of influence, and another polar High started to descend from the north, a

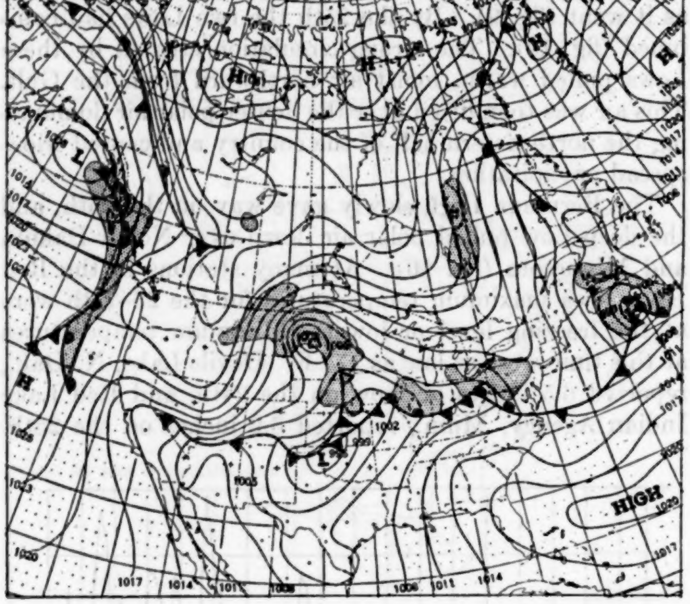

FIGURE 9.—Surface weather map for 0630 CST, April 24, 1950. Shading indicates areas of active precipitation.

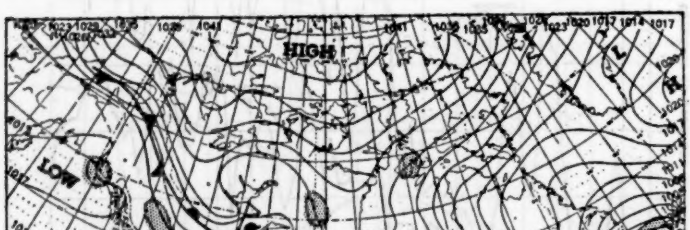

FIGURE 10.—Surface weather map for 1230 CST, April 25, 1950.

FIGURE 11.—Surface weather map for 1230 CST, April 27, 1950.

new Low started to develop in Utah. The weather of May 8–9 was a repetition of the storm of May 4–6, with many stations reporting more than an inch of precipitation in the 2 days. During the first 9 days of May many stations recorded more than 3 inches of precipitation; Sharon, N. Dak., and Trail, Minn., each reported more than 5 inches.

The Pacific High advanced into the United States behind the eastward moving Low and on May 10 extended as far as the Red River Valley. It dominated the circulation over the Basin until early afternoon of the 11th, when a Canadian High moved down over most of the Red River of the North. Then, as a frontal system passed to the east of the Basin on the 13th, the Pacific High pressed eastward over the area for a brief period.

On the 15th, polar air once more invaded the Red River Valley, and temperatures which had soared briefly sank again. Polar air remained over the Basin until the morning of the 18th, when an active Pacific front approached (fig. 12). A strong flow from the south aloft over the Red River area at this time indicated that warm air was overrunning the cold. Many stations in the region reported more than an inch of precipitation during the short period between the front's approach and passage.

Very little precipitation occurred during the remaining part of May, as the Valley was dominated first by the Pacific High, then by the polar High from Canada. On the last day of the month polar air again invaded the Red River Valley.

The troughs and ridges in the general circulation pattern of June were located slightly west of those for the preceding month, resulting in a corresponding shift in surface temperature anomalies. (See Aubert [4].) Although not so simply related to the general circulation, there were also changes in precipitation anomaly patterns. Precipitation in June was slightly above normal in northern Minnesota, although in eastern North Dakota precipitation averaged a little below normal. The record-breaking spring flood in the lower Red River of the North continued in the month of June.

On June 2, a cold front from Canada moved southeastward across the North Dakota-Minnesota region with a great High behind it. The High settled in the Great Basin and controlled the circulation of the major part of the country through the 5th.

FIGURE 12.—Surface weather map for 1230 CST, May 18, 1950.

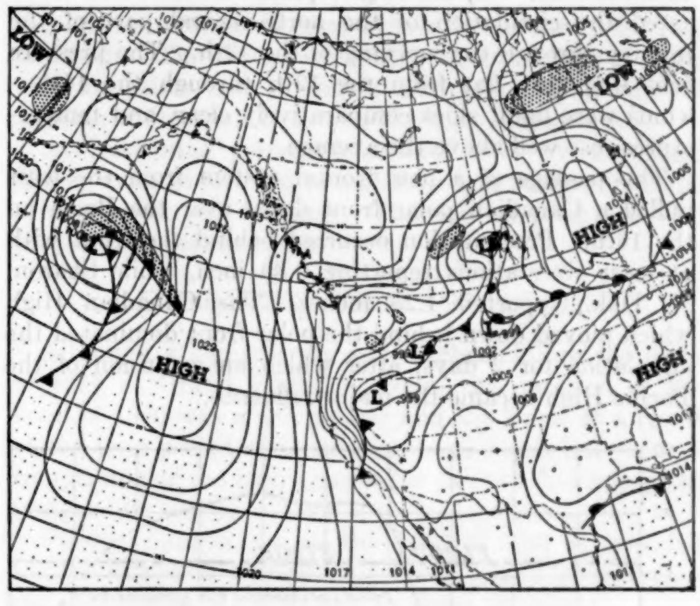

FIGURE 13.—Surface weather map for 0930 CST, June 6, 1950.

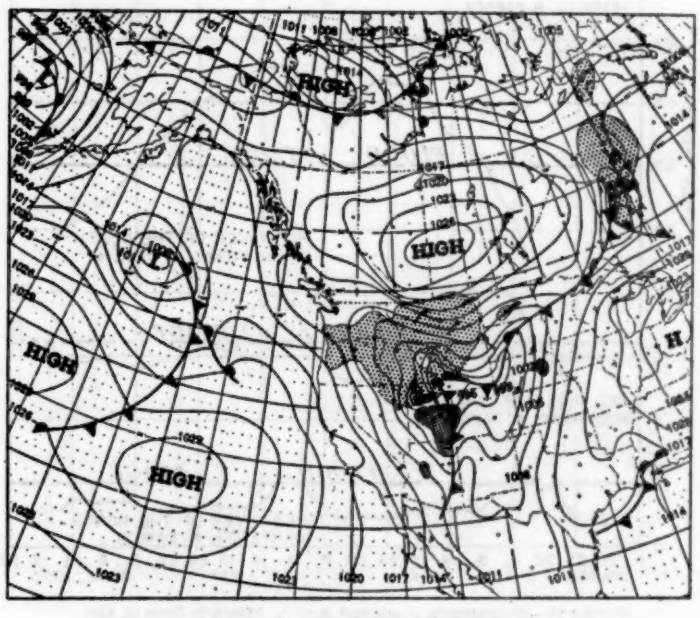

FIGURE 14.—Surface weather map for 0930 CST, June 7, 1950.

On the 6th, a strong frontal system approached the Red River Basin from the west. The front lay in a low pressure trough that extended southwestward over the Plateau, where a Low was developing over the Nevada-Idaho-Utah area. (See fig. 13.) The Low resulted in the lowest pressure on record for June for points in Nevada and Utah (see O'Connor and Norton [5]), and on the 7th its strong circulation pulled warm, moist air up from the south and lifted it over the cold dense air that had invaded the Valley of the Red River of the North (fig. 14). Many stations on the North Dakota side of the Basin received more than half an inch of rain as a result of this activity.

The Low traveled north-northeastward at a slow pace, releasing precipitation intermittently over the River Basin until the 10th. A polar High replaced the Low and dominated the circulation of the north-central part of the country through the morning of the 12th. The pressure field was very flat from the 12th through the 14th—winds were light, skies comparatively clear, and temperatures rose well above the average.

The passage of a new frontal system from the west pulled a Canadian polar front down over the Basin on the 16th. Precipitation occurred behind the front with at least six stations reporting 0.80 inch, while Sharon, N. Dak., reported 1.25 inches. The Canadian High which moved down behind the polar front dominated the circulation for 2 days, after which an extension of the Pacific High became the major influence.

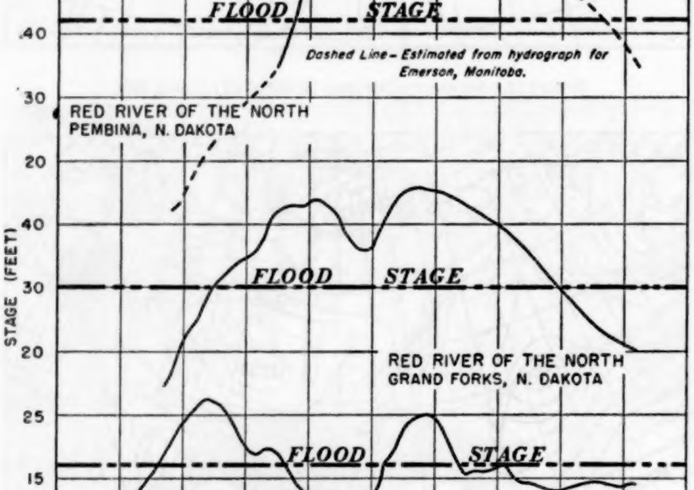

FIGURE 15.—Hydrographs at selected stations, March 24–June 15, 1950.

On June 21, a frontal system from the Pacific lay through central Montana, its Low north of the Canadian border. The frontal system moved eastward slowly while the Low in south-central Canada deepened rapidly. The Pacific cold front swept past the Red River Basin area late on the 22d, and on the 23d the intense cyclonic circulation pulled a polar front from Canada down across the North Dakota-Minnesota region.

The Low in Canada now moved rapidly northeastward, but low pressure started to develop in the Great Basin. The strong cyclonic circulation halted the front just past the River Basin area and pulled warm air laden with moisture up from the south. Precipitation resulted at many stations but much greater amounts were reported on the following day as the Great Basin Low deepened and moved rapidly northeastward. The combination of strong overrunning and sharp cyclonic turning resulted in such rainfall totals as 6 inches at the Fosston Power Plant, Minn.; 6.50 inches at Leonard, Minn.; and 4.10 inches at Mahnomen, Minn.

The passage of this Low brought an extension of the Pacific High deep into the United States where it governed the weather until the passage of a minor polar front on the 27th. The High which followed behind the front controlled the weather of the Red River of the North until the end of the month.

FLOOD OF 1950

The preceding discussion of meteorological conditions shows that the record flooding of the Red River of the North during the spring of 1950 was due to a combination of several factors, namely, heavy snowfall accumulation during the winter, late break-up or prolonged cold weather in the spring, and moderate to heavy precipitation near the time of break-up.

Flooding began along the Red River of the North at Wahpeton, N. Dak., and Fargo-Moorhead on March 31, spreading downstream to Grand Forks, N. Dak., by April 10 (see fig. 15). It reached a crest of 11.92 feet at Wahpeton, N. Dak., on April 2, slightly higher than the 1947 flood but considerably lower than the 1943 and 1897 floods. (Table 1 gives a résumé of the duration of the

TABLE 1.—*Duration and crest stages of 1950 flood of the Red River of the North*

Station	Dates above flood stage 1950		Duration of flood (days)	Flood stage (feet)	Crest date	Crest stage (feet)
	From—	To—				
Wahpeton, N. Dak	Mar. 31	Apr. 4	5	10	Apr. 3	11.9
	May 9	May 11	3		May 10	11.9
Moorhead, Minn	Mar. 31	Apr. 20	21	17	Apr. 8	27.2
	May 6	May 18	13		May 13	24.9
Grand Forks, N. Dak	Apr. 7	June 4	59	30	Apr. 25	43.9
					May 12	45.8
Pembina, N. Dak	Apr. 21	*June 10	51	42	May 1	51.7
					May 14	52.9

*Interpolated from hydrograph for Emerson, Manitoba.

TABLE 2.—*Comparative crest stage data of major floods of the Red River of the North*

Station	Flood stage (feet)	1897		1916		1920		1943		1947		1948		1950		Highest of record	
		Stage (feet)	Date	Stage (feet)	Date	Stage (feet)	Date	Stage (feet)	Date	Stage (feet)	Date	Stage (feet)	Date	Stage (feet)	Date	Stage (feet)	Date
Wahpeton, N. Dak.	10	†19.0	4/—/1897	------	------	------	------	*14.75	4/2/43	11.9	4/12/47	8.6	4/6/48	11.9	{4/3/50 5/10/50}	†19.0	April —, 1897.
Moorhead, Minn.	17	†40.1	4/7/1897	31.2	4/6/16	23.6	3/28/20	34.3	4/7/43	28.9	4/15/47	18.0	4/10/48	27.2	4/8/50	†40.1	April 7, 1897.
Grand Forks, N. Dak.	30	50.2	4/10/1897	41.0	4/17/16	41.0	3/29/20	38.2	4/12/43	40.7	4/22/47	41.7	4/16/48	43.9 45.8	4/25/50 5/12–13/50	50.2	April 10, 1897.
Drayton, N. Dak.	------	#41	4/—/1897	------	------	------	------	33.7	4/17–19/43	33.1	4/28/47	40.05	4/22/48	40.9 41.6	4/26/50 5/12/50	41.6	May 12, 1950.
Pembina, N. Dak.	42	------	------	------	------	------	------	------	------	------	------	**48.5	4/27/48	51.7 52.9	5/1/50 5/14/50	52.9	May 14, 1950.
Emerson, Manitoba.	------	‡791.2	4/—/1897	785.16	4/24/16	------	------	776.97	4/20–21/43	775.50	5/1/47	787.41	4/27/48	790.6 791.7	4/30/50 5/16–17/50	791.7	May 16–17, 1950.

† Prior to gage records.
*Highwater mark.
#From marks furnished by local residents.
**Estimated from data for Emerson, Manitoba.
‡Above mean sea level.

1950 flood and height of crests on the Red River of the North and table 2 gives comparative crest stage data of all major floods on the river.) The crest moved downstream about 14 miles per day in the reach above Moorhead, Minn., reaching Fargo-Moorhead on April 8 at a stage of 27.2 feet, 1.7 feet lower than in the flood of 1947 and considerably lower than the record flood of 1897. In the reach between Moorhead, Minn. and Grand Forks, N. Dak., the crest movement slowed down to less than 10 miles per day reaching Grand Forks, N. Dak., on April 25 at a stage of 43.9 feet, the highest level since 1897. Red Lake River, a tributary of the Red on the Minnesota side above Grand Forks, reached a crest of 24 feet at Crookston, Minn., on April 23. Here the dikes were overtopped causing water to flow across low areas of the city. Approximately 75 city blocks of the residential area of Crookston were inundated and about 150 families evacuated. The flood moved downstream to the international boundary by the end of April, reaching a stage of 51.7 feet at Pembina, N. Dak., the highest stage in the history of the station.

While the first crest was reaching Pembina, N. Dak., a second rise was developing in the reach between Moorhead, Minn., and the confluence of the Bois des Sioux and Ottertail Rivers from the steady rains and additional snowfall during the first few days of May. By May 8, 2 to 3 inches of additional moisture had accumulated. The maximum temperatures during the first 7 days of the month ranged from 40° to 50° F. over the southern portion of the basin; by May 11, a high of 70° F. was recorded.

The runoff was particularly heavy from all of the tributaries in Minnesota which flow into the Red of the North. Flooding was extremely severe along the Red Lake River at Crookston, Minn., with the crests on May 7 (25.3 feet) and May 10 (24.8 feet) higher than the first crest of 24.0 feet on April 23. The crests along the main stem of the Red of the North from Grand Forks to Pembina, N. Dak., were from 1 to 2 feet higher than in April. The river receded only 0.7 foot at Pembina, N. Dak., during the first 6 days of May before beginning its second rise to a record crest of 52.9 feet between the 12th and 14th. The flooded areas were reported up to 30 miles wide in places near Pembina and generally around 10 miles in width from Drayton, N. Dak., northward.

At least nine persons lost their lives by drowning. Heavy damage resulted to highways and bridges from the severe prolonged flooding. The loss of livestock and property was tremendous.

COMPARISON WITH 1897 FLOOD

Although a higher crest was reached during the flood of 1897 at Grand Forks, N. Dak., the duration of the flood of 1950 was much greater and the losses as a result of the long period of inundation were much heavier. A comparison of the hydrographs for the two floods is given in figure 16.

Further information on the flood of 1897 is provided by the following newspaper account which appeared in the *Globe* at St. Paul, Minn., on April 10, 1897:

GRAND FORKS, N. D., April 9.—From 3 to 5 o'clock this afternoon the water receded one inch * * *. Since that time, the rise

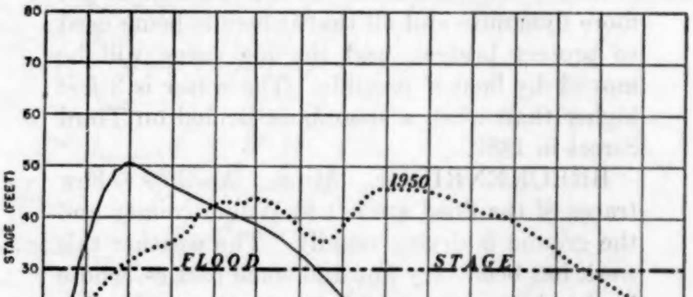

FIGURE 16.—Hydrographs at Grand Forks, N. Dak., April 1–May 31, 1897, and April 1–June 14, 1950.

amounts to more than half an inch an hour * * *. The water is almost on to Third Street, and, if the rise continues during the night, it will leave 25 blocks of paving on that street under water. So far but two and a half blocks of paving are ruined. The bridges at Minnesota Point are badly wrecked and are only kept from seeking the bottom of the river by strong cables. Both railroad bridges are wrecked somewhat, and men have been stationed on the structures for several hours shattering the larger pieces of ice with dynamite before the bridges are struck. Ice continued to run until a late hour tonight, and a big gorge is held back by the approach to the Great Northern.

A dozen reports have reached here from points below the city of whole families huddled on top of haystacks or houses, together with livestock, and with no way to get away. Barges were floated 2 miles down, and a family and a large amount of stock were saved, and it was none too soon. English Coulee has filled today and covers an area of several miles, taking a Northern Pacific bridge away. Farmers in that section are on the higher ground, and they will be unable to extricate themselves until a boat is sent down the river * * *

Seven miles north of the city the ice has formed a gorge 2 miles long and this is probably holding much of the water, and an effort will be made to move it. Business is suspended in East Grand Forks in all but half a dozen places, and traffic between the two cities is suspended. An ice pier of one bridge went out today and the structure has been badly damaged as a result. An immense amount of damage has already been done, but, if the water continues at the present rate until morning, it will reach an enormous sum. It is impossible to get more dynamite and all that is here is being used to protect bridges, and the big gorge will be moved by boat if possible. The water is 3 feet higher than when a steamboat landed on Third Street in 1882.

BRECKENRIDGE, Minn., April 9.—Few traces of the flood are left in Wilkin county and the ground is drying rapidly. The weather this week has been very fine and some parties, whose land is high, expect to begin seeding early next week.

FARGO, N. D., April 9.—The water continues to fall steadily and the city looks much as the neighborhood of Ararat must have looked after the deluge.

PEMBINA, N. D., April 9.—Since noon yesterday the water has risen about 4.5 feet in the Red. It will reach its height about the 18th of April, judging from the level above and the conditions of the stream.

BUSTON, N. D., April 9.—The mail carriers from Belmont, 10 miles east of here, on the Red River, bring serious reports of the flood at that place. Belmont was established as a trading post by the Hudson Bay Co. The site selected is the highest ground between Lake Traverse and Winnipeg Lake, and was supposed to be above the reach of any flood. Up to this time this supposition has been correct. Today, however, all past records of high waters have been reached and passed, and the Red is steadily rising at the rate of a foot an hour. The water has reached Front Street, and is on a level with the buildings. * * * With every tributary from Lake Traverse to Grand Forks a raging torrent, and the lower river still solid, it is feared that tremendous ice gorges will be formed which would flood the entire valley with backwater.

ACKNOWLEDGMENTS

Acknowledgment is due Mr. Bennett Swenson, chief, River Services Section for initiating this study and for his suggestions and guidance in the preparation of this report; to James E. Caskey, Jr., editor of the Monthly Weather Review for his suggestions and comments; to Lillian K. Rubin, Hydrometeorological Section for her analysis of the meteorological situation (critical period weather); and to Ralph W. Shultz, Weather Bureau Office, Fargo, N. Dak., for forwarding data on the flood. Special acknowledgment is due the U. S. Geological Survey Office, Bismarck, N. Dak., for their cooperation in furnishing the Fargo Weather Bureau Office the current river stages and comparative river stage data for their stations.

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THE WEATHER AND CIRCULATION OF SEPTEMBER 1951[1]

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The 700-mb. circulation pattern for the month of September (fig. 1) shows that North American weather was dominated by a ridge extending southward from the Yukon along and off the Pacific Coast to about 45° N. and an accompanying trough to its east reaching from Kansas to Baffin Island. Off either coast of the southern United States was a weak secondary trough. These two troughs were separated by a High centered in the northern Bahamas with a stronger than normal ridge line extending west-northwestward through the northern Gulf of Mexico, central Texas, and southern New Mexico and Arizona. Thus, troughs and ridges at high latitudes were out of phase with those at lower latitudes. As a result, the confluence of contrasting air masses [1] was a prominent feature of the September pattern, more or less as it had been all summer [2, 3, 4]. The axis of confluence in the central United States was accompanied by stronger than normal westerlies downstream across eastern North America and the Atlantic Ocean.

In this fast westerly flow numerous cyclones sped eastward, deepening as they approached the central Atlantic trough (Chart X). These cyclones were both deeper and farther south than usual for September, as indicated by the large negative departures from normal of both 700-mb. height (fig. 1) and mean sea level pressure (Chart XI

[1] See Charts I-XV following p. 187 for analyzed climatological data for the month.

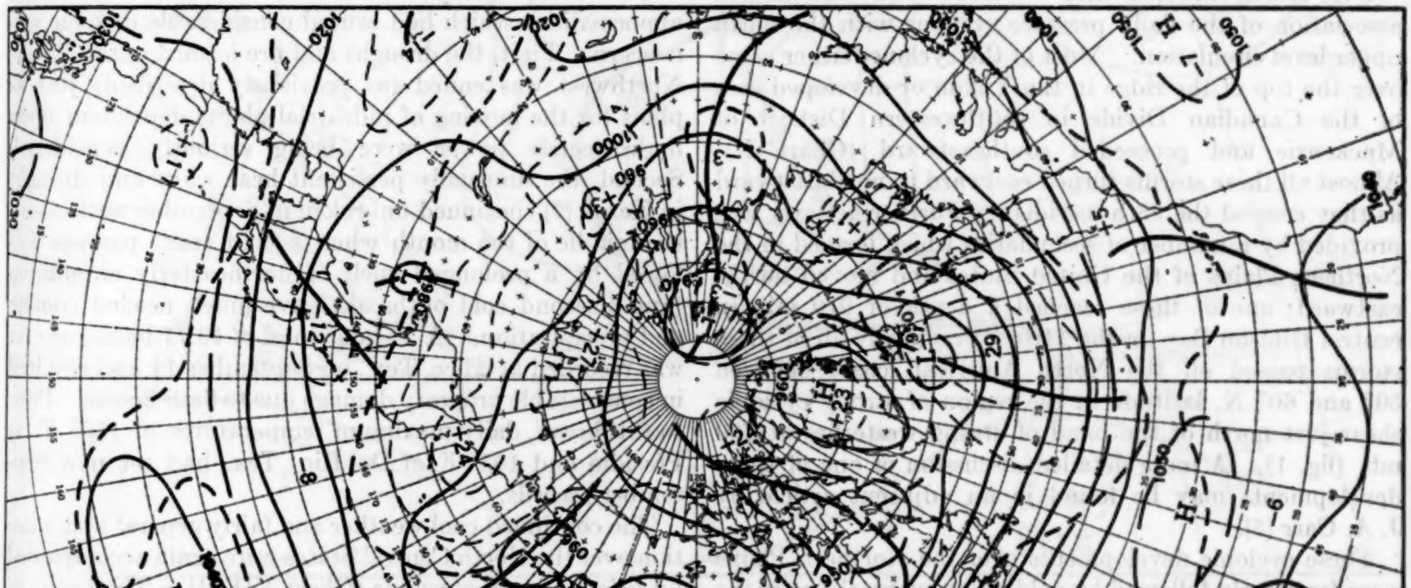

FIGURE 1.—Mean 700-mb. chart for 30-day period August 31–September 30, 1951. Contours at 200-foot intervals are shown by solid lines, intermediate contours by lines with long dashes, and 700-mb. height departures from normal at 100-foot intervals by lines with short dashes with the zero isopleth heavier. Anomaly centers and contours are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

inset) south of the normal storm path and centered just to the south of Iceland. This area of persistent cyclonic activity reached its climax on September 11 when a low of tropical origin (hurricane "Fox") was reported to be of 963-mb. intensity southwest of Iceland. Climatological records for the area indicate that a September storm of this depth occurs about once in 10 years.

Cyclonic activity was also well marked in the eastern Pacific trough, but only a few storms managed to break through the mean ridge along the west coast of North America. Many of the Lows stalled and filled as they approached the ridge, while not infrequently northerly and northwesterly trajectories were taken by other storms skirting its periphery (Chart X). The ridge was remarkably persistent until the last decade during which it retrograded rapidly. When, in the course of this retrogression, the ridge reached the Bering Sea, cold Arctic air poured down its eastern side into the Gulf of Alaska where rapid cyclogenesis occurred. At least two storms entered the Pacific Northwest during the latter stage of this development and effected a much needed relief after prolonged drought in this area.

Over North America there was a broad but well defined association of the daily pressure systems with the mean upper level circulation. Most of the cyclones either came over the top of the ridge in the Yukon or developed east of the Canadian Divide in southwestern District of Mackenzie and proceeded southeastward (Chart X). Almost all these storms turned eastward to northeastward as they crossed the 95th meridian. Further activity was provided by a number of secondaries which formed in the Northern Plains of the United States and moved northeastward; one of these reached a depth of 970 mb. in central Hudson Bay on the 14th. Practically all of these storms passed off the North American coast between 50° and 60° N. latitude in the region of strong cyclonic shear just north of the band of strong westerlies at 700 mb. (fig. 1). A more detailed discussion of one of these developments may be found in an adjacent article by J. A. Carr [5].

These cyclonic developments over the Northern Plains were frequently followed by cold polar outbreaks over the north central area of the United States. The accompanying major anticyclone track was from western Canada southeastward across the Northern and Central Plains and eastward through the northeastern States (Chart IX). The difference in latitude between the mean cyclone and anticyclone tracks is especially well defined in eastern North America where very little overlapping is indicated (compare Charts IX and X). Particularly conspicuous is the lack of normal cyclonic activity in the northeastern United States.

This regime produced a mean temperature anomaly pattern which seems to be becoming quite familiar. Chart I-B shows the continued dominance of below-normal temperature from the northern border of the United States, between the Continental Divide and the Appalachians, southward to Oklahoma, Arkansas, and mid-Tennessee. The remainder of the country, with very minor exceptions, was above normal in temperature with greatest departures in southern Nevada and the lower Colorado River Valley. At Yuma a new record was set when the mean September temperature equalled 90.6° F. Texas still averaged above normal but in the eastern sections of the State the mean temperature anomaly was smaller than in previous months. The greatest negative departures were observed in southeastern Montana where temperatures averaged close to 6° F. below normal.

Precipitation exceeded the seasonal normal (Chart III) in a wide band extending from northern Washington and Idaho through most of the northern Rocky Mountain States, Central Plains, lower Mississippi Valley, and the Southeast. The driest area was New Mexico where the State precipitation average was only 15 percent of normal and soils were reported too dry for the planting of winter grain. The Middle Atlantic States and most of New England also reported below-normal rainfall. Virginia had the driest September in 10 years and in some localities it was considered the worst drought in 20 years.

Two areas finally experienced relief from prolonged abnormalities which had caused considerable damage and concern. First, the drought and fire hazard in the Pacific Northwest was ended (as previously described) just as plans for the moving of industrial plants dependent upon hydroelectric power were being seriously considered. Second, the unusually persistent heat wave and drought in Texas [2] continued unbroken in September until about the middle of the month when a cold front passage followed by a prolonged spell of northeasterly circulation (and a second cold outbreak) gave much needed cooling and precipitation. A 24-hour total of 13.77 inches of rain was recorded at Alice, Tex., on September 14 and resulted in considerable property damage due to flash floods. Prior to this break, daily maximum temperatures of 110° F. at Presidio and 105° F. at Del Rio, Tex., had set new September records.

The continued cool weather and fairly general precipitation over the North Central States were again accompanied by below-normal sunshine (Chart VII-B). The result of this regime was the slow maturation of crops, particularly the Iowa corn crop. A hard freeze on the 28th (21° F. recorded at Inwood) caused widespread damage except for local areas in the eastern and southeastern portions of the State. One-third of the crop was estimated to be vulnerable, and losses were proportional to the severity of the local freeze. It was ironical that the cold spell was of very short duration, and temperatures soared to a State high of 91° F. by October 1.

Just as ironical, but in a much more felicitous vein, was the diversion which spared Bermuda serious hurricane damage. Figure 2 shows the tracks of Atlantic hurricanes "Easy" and "Fox" as related to the 5-day mean 700-mb. pattern. "Easy" was turning northward from the 7th to the 8th as a polar trough moved off the east coast of the

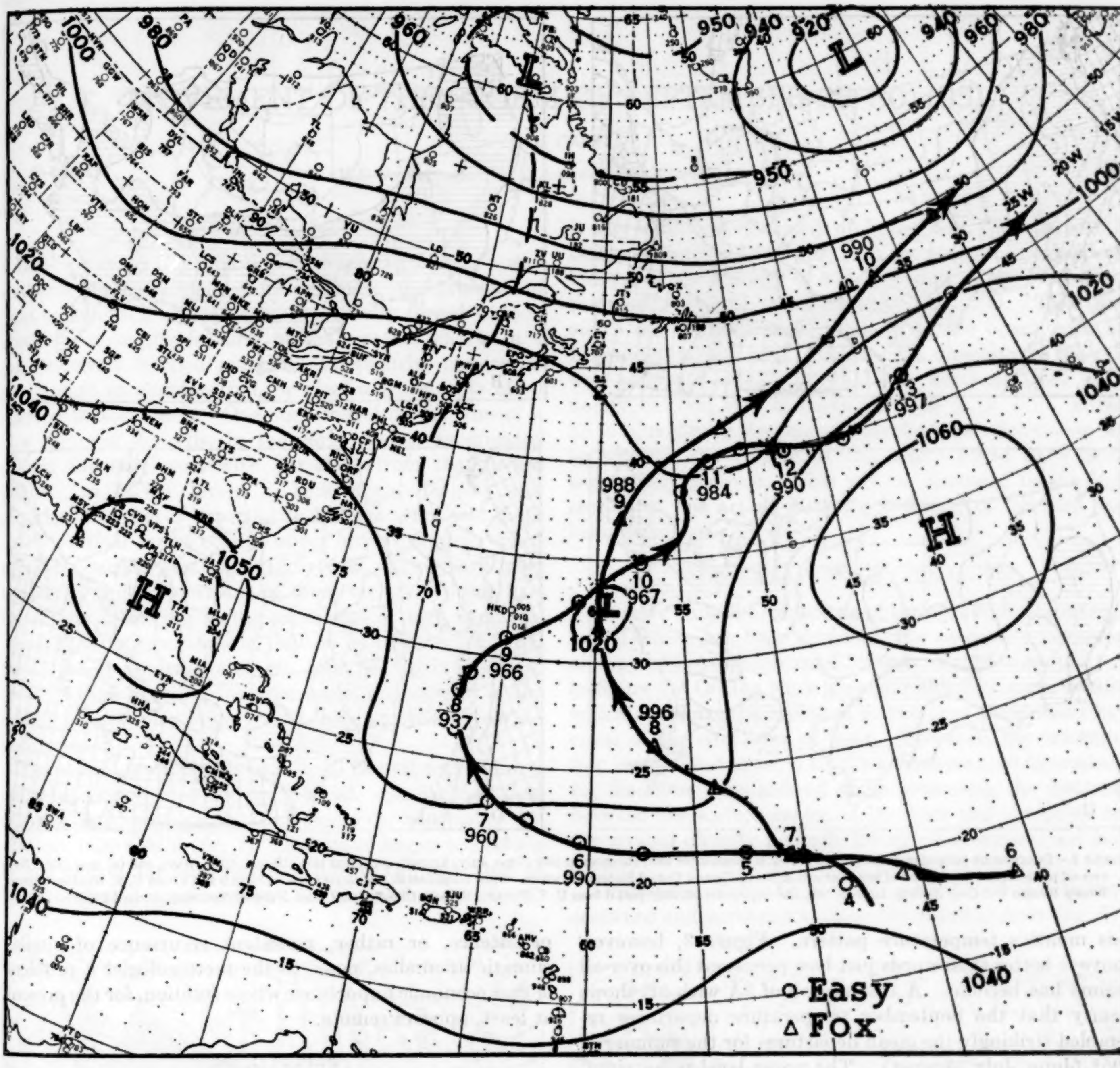

FIGURE 2.—Tracks of hurricanes "Easy" and "Fox" superimposed on 5-day mean 700-mb. contours for period September 8-12, 1951. Date and approximate intensity (in millibars) at storm center are given for 1230 GMT positions, with 0030 GMT positions also indicated by circles for "Easy" and triangles for "Fox". Dashed line along 70th meridian indicates position of mean trough one-half week previously. Contours are labeled in tens of feet.

United States. Hurricane "Fox" was not far behind and traveling northwestward somewhat faster than "Easy" as it was still steered by the warm anticyclone to its north-northeast. With the approach of the polar trough it too began to recurve, however, at a faster rate and farther east than "Easy." On the morning of the 9th, "Fox" was still the weaker of the two storms and centered east-northeast of Bermuda, while "Easy" was somewhat the stronger and almost south of Bermuda. The interactions of the two circulations weakened the circulation around "Easy" and accelerated its eastward component of motion. The storm passed within a hundred miles of Bermuda but instead of the commonly anticipated hurricane speeds only moderately high winds were observed. Presumably the weakening of "Easy" from the 8th to the 9th and its eastward acceleration due to the intervention of "Fox" were all that prevented serious damage to Bermuda. More intensive studies of this situation will undoubtedly be forthcoming.[2] In all, it should be accounted one of those fortuitous interactions which are certainly not uncommon but which seldom appear to be so timely and spectacular.

Mention has already been made of the familiar aspect of

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[2] A brief discussion of these and other recent hurricanes appears in *Weatherwise*, vol. 4, No. 5, October 1951, pp. 105-106.

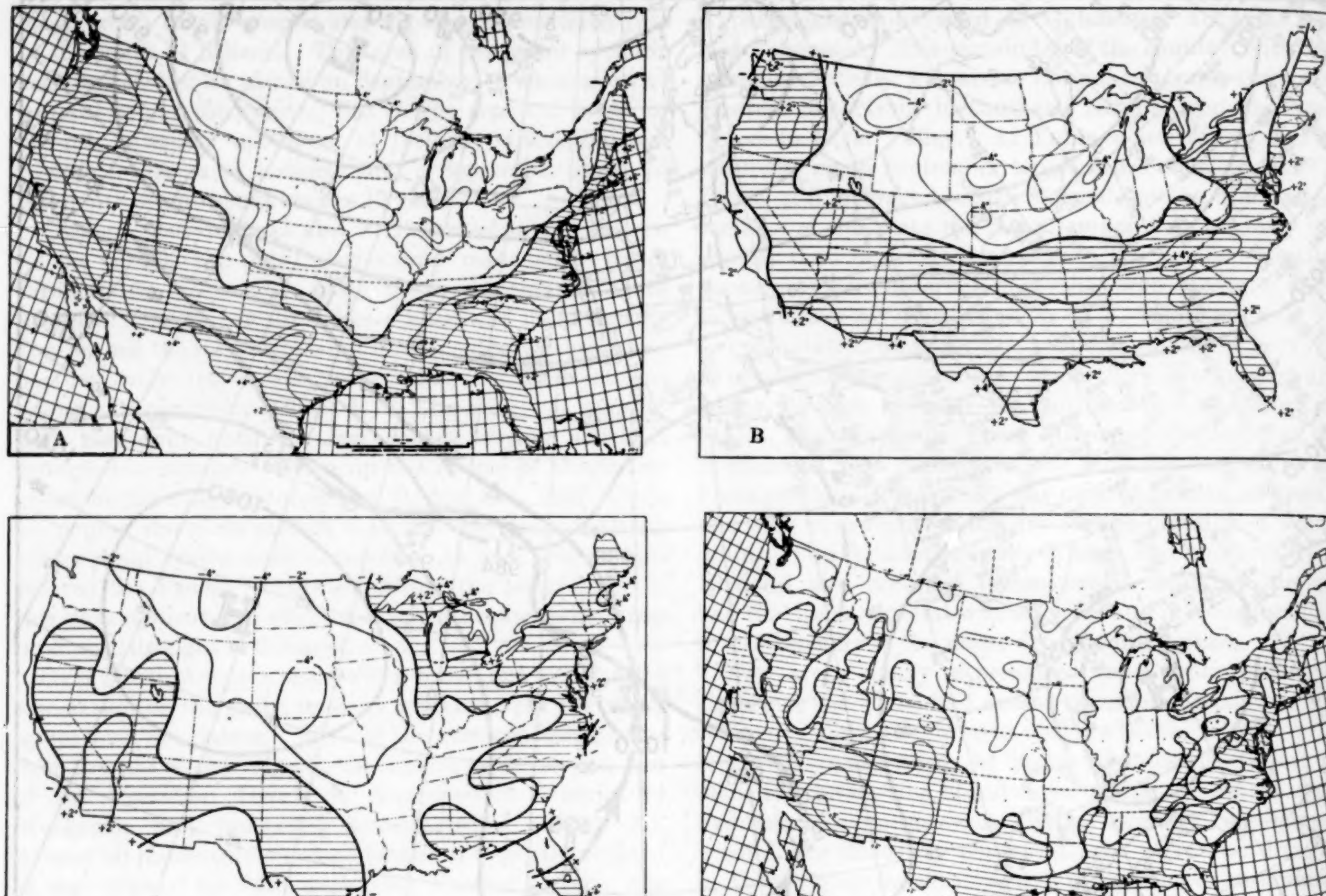

FIGURE 3.—Temperature anomalies in the United States, (a) September 1951, (b) summer 1951 (June, July, August), (c) spring 1951 (March, April, May), and (d) year 1950. Not over-all persistence of below-normal temperatures in North Central United States with above-normal anomalies in peripheral areas. (Parts b and c from U. S. Weather Bureau *Weekly Weather and Crop Bulletin*, June 12, 1951, and September 18, 1951; part d from U. S. Weather Bureau, *Climatological Data, National Summary*, Annual 1950.)

this month's temperature pattern. Figure 3, however, conveys better than words just how persistent this over-all regime has become. A comparison of 3A with 3B shows clearly that the September temperature departures resembled strikingly the mean departures for the summer of 1951 (June, July, August). The upper level mean circulation patterns during this period were dominated by a ridge in the eastern Gulf of Alaska or western Canada which caused frequent cold air intrusions in the North Central United States. Fluctuations in the position and intensity of the trough downstream and the Bermuda High (particularly the westward ridge extension) allowed considerably wider variations in the precipitation pattern (not shown), but many features of the September precipitation pattern also resemble the pattern observed during the summer.

Furthermore, the spring of 1951 had a similar temperature pattern (fig. 3C). The basic mean circulation pattern of spring likewise contained much the same dominant features over North America. Still more amazing is the similarity of the over-all temperature anomaly for the entire year 1950 shown in figure 3D. Such long period persistence, or rather, persistent recurrence of similar climatic anomalies, poses to the meteorologist a problem of vast economic importance whose solution, for the present at least, appears remote.

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MOVEMENT OF THE STORM OF SEPTEMBER 25–30, 1951

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INTRODUCTION

In the day to day practice of preparing forecasts and analyses, meteorologists, working under the pressure of tight schedules and deadlines, are usually forced to look upon the changing features of the weather charts in a comparatively hurried manner. Frequently, meteorologists resort to standardized, or idealized, concepts often referred to as models. One such model of the core of a Low pictures the axis, in the early stages, as oriented toward the northwest with flat slope from the surface position to higher levels; as the storm deepens and occludes, the axis is expected to become more and more nearly vertical as the core at upper levels gradually overtakes the surface position. Individual storms vary from the model and a knowledge of these variations leads to a better understanding of the usefulness of such a device. The following presentation, limited as it is to one case, the storm of September 25–30, 1951, is not intended to do more than examine the orientation and motion of the axis of a particular storm which became well developed and occluded.

The storm developed from a small frontal wave with a central pressure of 1,000 mb. which was located over extreme southwestern South Dakota on September 25, 1951, at 1830 GMT (fig. 1). The wave began to occlude by the end of the first day and during the following 24 hours deepened considerably. On September 27 (fig. 2) it was southwest of the tip of James Bay, Canada, with a central pressure of 982 mb. On the 30th, the center was located in the vicinity of 60° N. Lat. and 50° W. Long., practically unchanged in strength (987 mb). Thus the storm moved from South Dakota to the ocean, east of Labrador, in just over 5 days. Its direction of motion was almost constantly toward the northeast and at a nearly uniform rate of movement (19 m. p. h.). These facts plus strong deepening provoked the speculation as to whether the motion of this storm could have been successfully forecast. This will be discussed in the last section of this article after the behavior of the core has been examined.

THE BEHAVIOR OF THE CORE

To determine the variations of the core from the simple model which has been depicted, the successive positions of the surface, 700-mb., and 500-mb. centers were plotted in figure 3. On the work sheet for this figure are details which could not be included in the final illustration because of the confusion of lines. However, the information is embodied in table 1. The numbers used in expressing distances were arrived at by measuring the distance between the surface center of the Low and the point on the ground directly beneath the specified upper-level low center.

During the 25th, the new wave developed and moved eastward and northeastward across South Dakota (fig. 3).

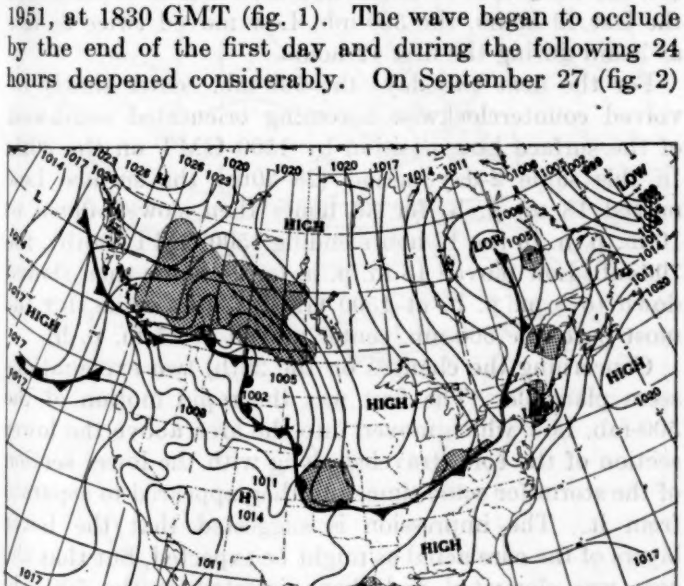

FIGURE 1.—Surface weather chart, 1830 GMT, September 25, 1951. Shading indicates areas of active precipitation.

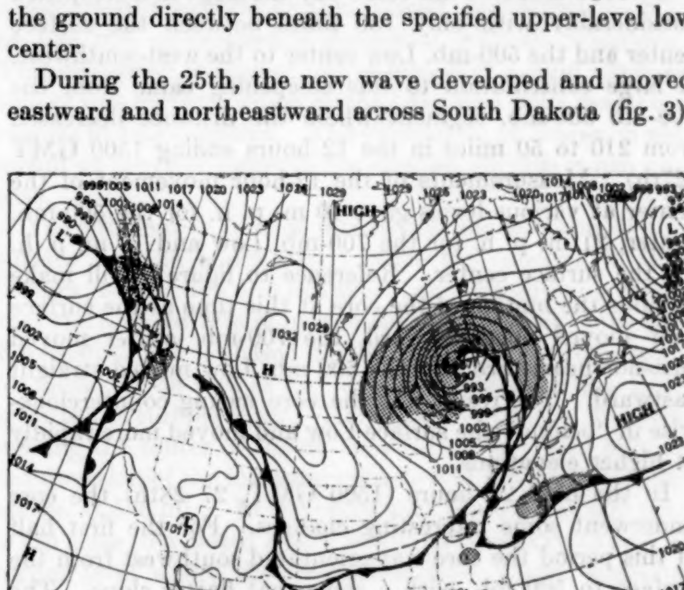

FIGURE 2.—Surface weather chart, 1830 GMT, September 27, 1951.

TABLE 1.—*Horizontal distance and orientation between various segments of the storm core (through the interval from surface to 500 mb.)*

	Time (GMT)	Surface to 700 mb.		700 mb. to 500 mb.		Surface to 500 mb.	
		Orientation	Distance (miles)	Orientation	Distance (miles)	Orientation	Distance (miles)
Sept. 26	03	NNW	630	----	----	----	----
	15	NW	450	NW	300	NW	750
27	03	WNW	220	WNW	210	WNW	430
	15	W	100	SW	50	WSW	150
28	03	SW	90	SW	130	SW	200
	15	None	0	NW	100	NW	100
29	03	None	0	WNW	110	WNW	110
	15	SW	30	WNW	130	W	150
30	03	W	80	W	100	W	180
	15	WSW	127	SW	90	SW	195

On this first day, the core of the storm could not be reliably identified above 700 mb.; however, it appeared to be inclined northwestward from the surface to 500 mb. At 0300 GMT (26th) the 700-mb. center was about 630 miles north-northwest of the surface low, and 12 hours later the orientation was about the same, but the distance had decreased to 450 miles (refer to table 1). At this time (1500 GMT, 26th) the surface Low was located to the southwest of St. Cloud, Minn., with a suggestion of a center at 500 mb. in the vicinity of Prince Albert, Saskatchewan, Canada. So far, observations seem to be in agreement with usual ideas on the subject. As the Low developed the core moved toward a more vertical position. At the end of the next 12 hours (0300 GMT, 27th) the surface Low was over Houghton, Mich., with its 700-mb. counterpart 220 miles to the west-northwest. With respect to the surface center, the 500-mb. low was 430 miles to the west-northwest.

By 1500 GMT of this same day the slope had steepened considerably with only 150 miles between the surface center and the 500-mb. Low center to the west-southwest. A large contribution to this steepening came from the 700- to 500-mb. segment where the distance decreased from 210 to 50 miles in the 12 hours ending 1500 GMT (27th). Measurements of the 12-hour movement of the center at various levels gave 40 m. p. h. for the 500-mb. center, 21 m. p. h. for the 700-mb. Low and 18 m. p. h. for the surface center. Reference to figure 3 will make obvious the motion of the core at this time as the surface Low moved northeastward, the 700-mb. center moved east-northeastward and the 500-mb. Low moved straight eastward. The result was the core swung counterclockwise in "behind" the surface Low and moved more rapidly at higher elevations.

In the next 24 hours (1500 GMT, 27–28th) the core underwent some interesting changes. For the first half of this period the core was orientated southwest from the surface to 500 mb. with a somewhat flatter slope. The surface to 700-mb. slope had become nearly vertical (90 miles) but the 700-mb. to 500-mb. distance had increased from 50 to 130 miles. The vertical gradient of horizontal speed changed during the 12 hours ending at 0300 GMT on the 28th as the 500-mb. center moved at 16 m. p. h. and the 700-mb. and the surface centers moved at 23 m. p. h. At the end of the next 12 hours (1500 GMT, 28th), the core was vertical up to 700 mb. and not far from vertical (100 miles) from the 700- to 500-mb. levels, but two changes had taken place: the core was now orientated northwest, as on the 26th, from 700- to 500-mb. with the surface Low moving at 18 m. p. h., the 700-mb. center moving at 25 m. p. h. and the 500-mb. Low at 35 m. p. h. In this period, the surface to 700-mb. core moved northeastward but the 700-mb. to 500-mb. segment moved, first, east of north and later north of east. In the last 12 hours, the 500-mb. Low moved twice as fast as it did during the first 12 hours.

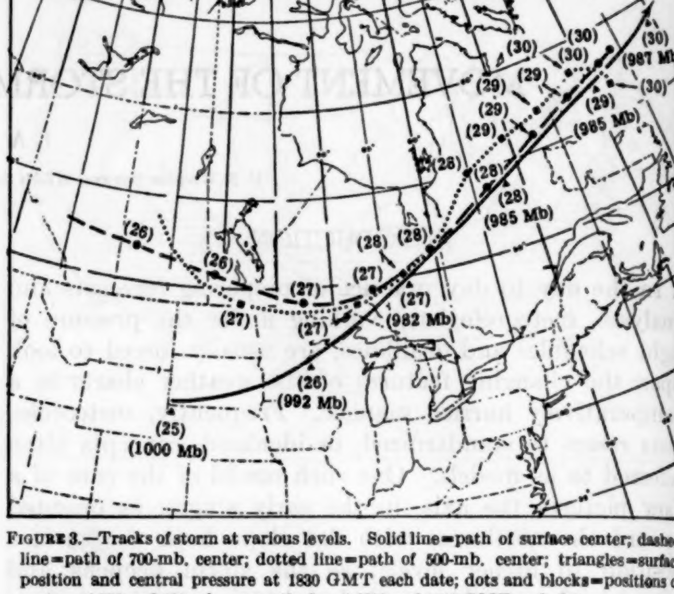

FIGURE 3.—Tracks of storm at various levels. Solid line=path of surface center; dashed line=path of 700-mb. center; dotted line=path of 500-mb. center; triangles=surface position and central pressure at 1830 GMT each date; dots and blocks=positions of centers at 700 and 500 mb., respectively, at 0300 and 1500 GMT each date.

For the next two days the 500-mb. center slowly revolved counterclockwise becoming orientated southwest of the surface Low position by 1500 GMT on the 30th. In this same 2-day period (28–30th) the surface Low moved 18 m. p. h. for 36 hours then slowed down to 10 m. p. h. in the 12 hours ending 1500 GMT (30th), the 700-mb. Low moved 18 m. p. h. for 24 hours then slowed down to 5 m. p. h. at 1500 GMT (30th) while, for the most part, the 500-mb. center moved at 15 m. p. h.

Concerning the changes on the 28th, two explanations seem plausible. The first was the rapid motion of the 500-mb. Low which moved into the area above the lower section of the core, traveled along with the lower section of the storm for some time, and then appeared to separate from it. The impression is suggested that the lower layers of the core acted as might be expected, but that the core was elongated and then distorted as the 500-mb. center described its seemingly independent course. Examination of various charts, including thickness charts, supported a second factor, that the activity of this period could be attributed to a fresh infusion of cold air which imparted new energy to the storm.

In effect, what took place on the 28th was a reorientation of the core from 700 to 500 mb. In connection with this idea of reorientation, the 300-mb. level was examined in the vicinity of the storm to discover what may have happened. A closed Low on the 0300 GMT chart (27th) between International Falls, Minn. and Fargo, N. Dak. was preceded by a broad tongue of warm air over lower Hudson Bay, as well as to the east of Hudson Bay. This wave of warm air had caused a 24-hour temperature increase of 9° C. at Nichequon, Quebec, Canada, after which the temperatures fell over all Quebec as a broad tongue of cold air swept in behind the wave of rising temperatures. Such a broad lid of cold air above an area of warm air necessarily worked to produce instability and in this way new energy could be made available to the storm.

OTHER ASPECTS OF THE STORM'S MOTION

In spite of various gyrations of the core, the surface Low described a remarkably smooth path across the surface of the earth. Except for the first 15 hours and the last 12 hours of its history the surface Low moved northeastward. Another feature was the uniform rate of motion of 18 to 19 m. p. m. for each 24-hour period during the 4 days until the storm left the North American continent, when it slowed down to about 12 m. p. h. A translation of its rate of movement into percentages of the geostrophic winds at 500 mb. (above the storm) shows that the surface center moved 63 percent the first day, 69 percent the next two days, and 64 percent on the fourth day.

The motion of the storm may be discussed in a slightly different fashion by comparing the path of the surface pressure changes with the path taken by the low center. The results show that the path of 24-hour pressure changes (falls) coincided with the surface path and provokes the speculation as to whether the direction of these falls could have been accurately forecasted. This will be discussed after the path of the 12-hour falls has been examined.

The path of the 12-hour falls presented somewhat less useful information. These falls on the 25th (1830 GMT) moved east across North Dakota, then southeast across Minnesota, followed by a recurving toward the northeast near La Crosse, Wis., to a location near Wausau, Wis., on the 26th (1830 GMT). So, over the early period of the storm, even a perfect forecast of the movement of the center of 12-hour falls would have yielded poor results, insofar as applying such information to forecasting the path of the surface Low was concerned. From the 26th (1830 GMT) to the 28th (1830 GMT) the fall centers traveled parallel to the surface storm track, but 90 miles to the southeast, from Wisconsin to the westernmost point of Labrador, Canada. After that point, the track of the 12-hour falls departed considerably from the storm track.

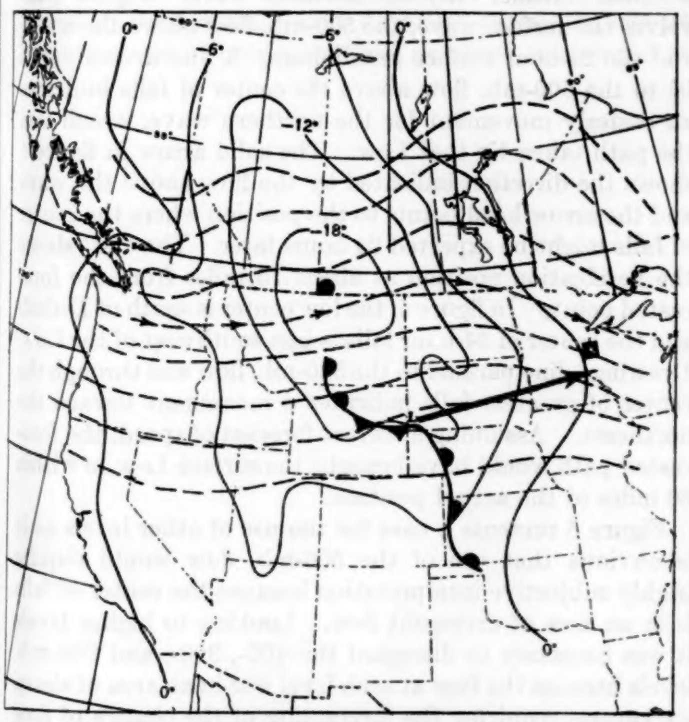

FIGURE 4.—Composite chart, 1830 GMT, September 25, 1951, showing surface fronts at 1830 GMT, 24-hour surface pressure falls (solid line at 6-mb. intervals) ending at 1830 GMT, and 500-mb. flow (broken line) at 1500 GMT. Arrow shows predicted direction (parallel to the 500-mb. flow); dot=center of 24-hour pressure falls; and blocked "X" =surface position of Low 24 hours later.

FORECASTING THE DIRECTION OF MOVEMENT

The remaining portion of this article will be concerned with a fundamental forecasting problem of foretelling the direction of movement of the surface center. There is considerable literature on this subject, but unfortunately, no one rule or method is successful with all situations. This discussion is limited to the results of a rigid application of one method which might have met with moderate success in this situation. The discussion, of course, is not meant to prove or disprove the method, for this is just one case.

The problem is that of forecasting the position of the surface Low 24 hours later. Since the concern, in this inquiry, is direction and not speed, an assumption is made that the forecast rate of movement is a "perfect" forecast. Forecasting will be based on the 1830 GMT surface map for each day as well as any upper air maps for the time prior to the surface chart. The system to be used involves moving the center of the 24-hour surface pressure falls in the direction of the instantaneous flow of the wind directly above, at 500 mb. In the event that the wind at 500 mb. is too close to a closed center it will be necessary to seek a higher level where the circulation more nearly suggests freedom from cyclonic flow. This is in agreement with usual practice. Furthermore, to make this a rigid application, no allowance will be made for anticipating the future flow pattern of the upper level winds, this to reduce the element of subjectivity and to eliminate the perspective of hindsight.

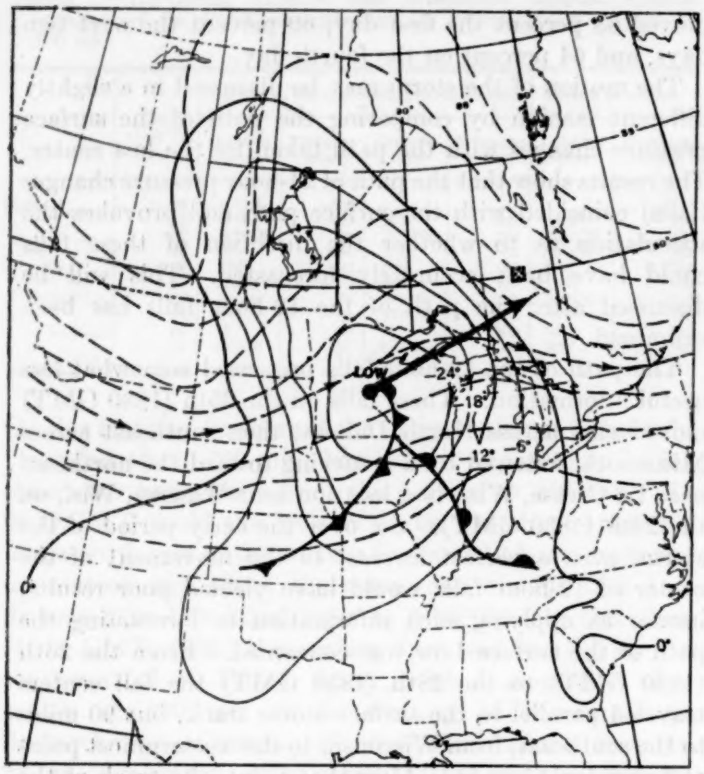

FIGURE 5.—Composite chart, 1830 GMT, September 26, 1951. Arrow is parallel to the 500-mb. flow.

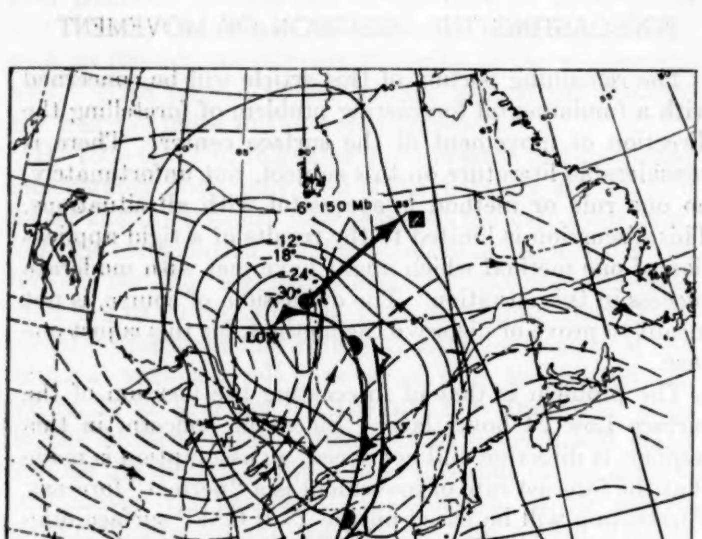

FIGURE 6.—Composite chart, 1830 GMT, September 27, 1951. Arrow is parallel to the 150-mb. flow.

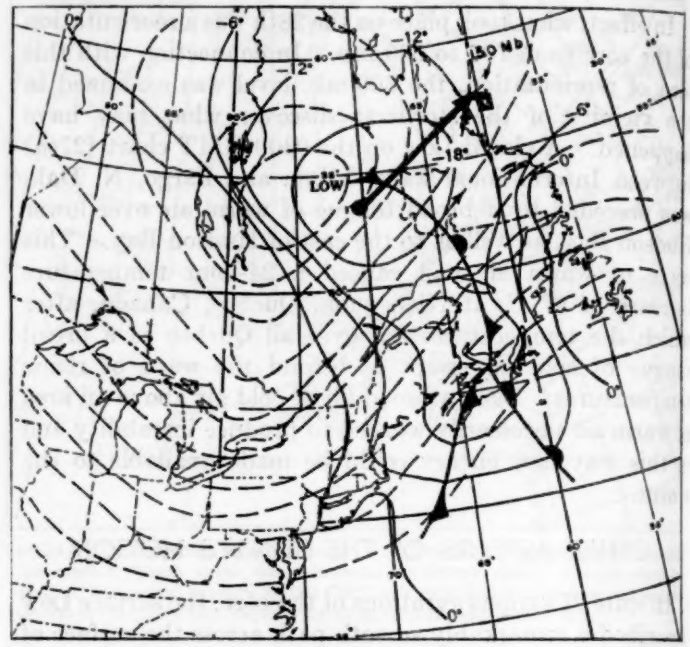

FIGURE 7.—Composite chart, 1830 GMT, September 28, 1951. Arrow is parallel to the 150-mb. flow

On the first day of the series it is evident that two waves are present, one being the subject of this article and the second being over north central Montana (fig. 1). During the next 24 to 30 hours the two centers moved along on just about parallel paths, after which the Montana wave lost its identity. So with this one application of hindsight we shall consider only the southern wave. Figure 4 involves the surface wave, the 500-mb. flow above the wave, and the 24-hour surface katallobars. A line drawn parallel to the 500-mb. flow above the center of falls indicates an easterly movement for the northern wave, which was the path taken by that Low. The solid arrow in figure 4 shows the direction indicated by the flow above the wave and the arrow head points to the position where the center of falls might be expected 24 hours later. The "X" shows the verification position at about 75 miles from the forecasted point. In figure 5, the low center is south of Duluth and the center of 24-hour falls is just southwest of the Low. Drawing a line parallel to the 500-mb. flow and through the center of greatest falls indicates a movement toward the northeast. Assuming a correct forecast of speed, the forecasted path would have brought the surface Low to within 60 miles of the actual position.

Figure 6 presents a case for the use of other levels as it is obvious that use of the 500-mb. flow would require highly subjective interpretation because the center of falls is in an area of divergent flow. Looking to higher levels it was necessary to disregard the 400-, 300-, and 200-mb. levels because the flow at each level was in an area of sharp curvature, requiring the forecasting of the change of flow in the forecast period. The 150-mb. level presented the first level of relatively "uninfluenced" flow and the direction

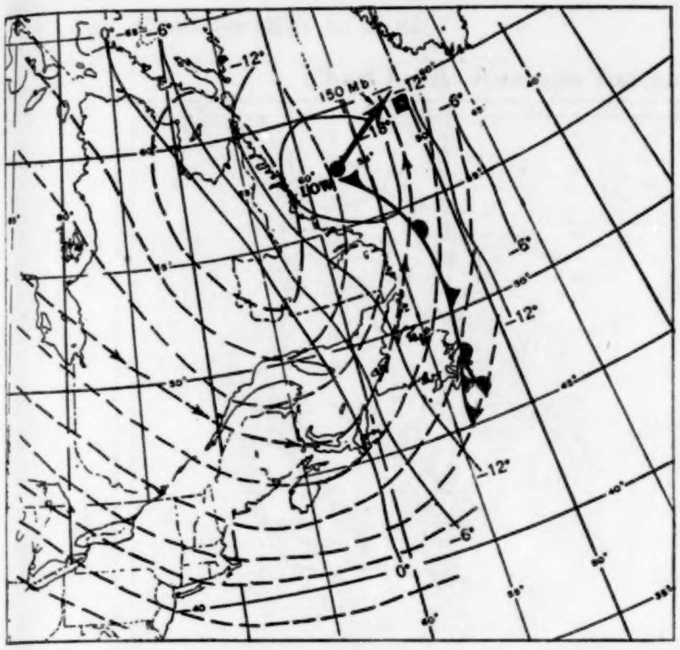

Figure 8.—Composite chart, 1830 GMT, September 29, 1951. Arrow is parallel to the 150-mb. flow.

indicated is in good agreement with the verification direction.

Concerning the above problem it might seem that the forecaster could be dubious of going to the 150-mb. level for a clue, but the following knowledge was available to him. At 1830 GMT of the 27th, a suggestion of the direction could be found by noting that the surface Low had moved to the northeast for 2 days and during the last 24 hours the rate of movement had remained unchanged at the surface. Since no blocking was evident, it seemed, therefore, that persistence would indicate continued movement toward the northeast as well as no change in rate of movement, thus bolstering the forecaster's confidence in the reliability of the 150-mb. indications.

By the 28th (fig. 7) the past history of the storm showed a 3-day northeast track at a steady rate of progression which lends greater weight to the influence of persistence. Although the flow at 500 mb. was once more without sharp curvature at a point above the 24-hour fall center, its use without question hardly seemed likely in view of the previous day's experience. Thus, the forecaster might be expected again to rely upon the 150-mb. flow where the indications were for continued movement in the direction given by persistence.

On the last forecast day (fig. 8), September 29, the following information was available: Persistence of direction and motion for 4 days, and previous success with the 150-mb. flow (direction). A straight application of the 150-mb. flow direction on this day indicated northeast motion. During this last day the rate of movement fell off to 12 m. p. h. and, employing persistence, the low center would have been moved too far by about 150 miles. The question can be raised as to whether the slowing down could have been anticipated. The answer could be a possible yes, if one were to fall back upon the climatological knowledge that Lows often slow down when approaching the coast of Greenland from west to southwest. Perhaps this question cannot be debated from the perspective of a later date, because it is possible that persistence would have weighed too heavily in the thinking of a forecaster on duty at that time.

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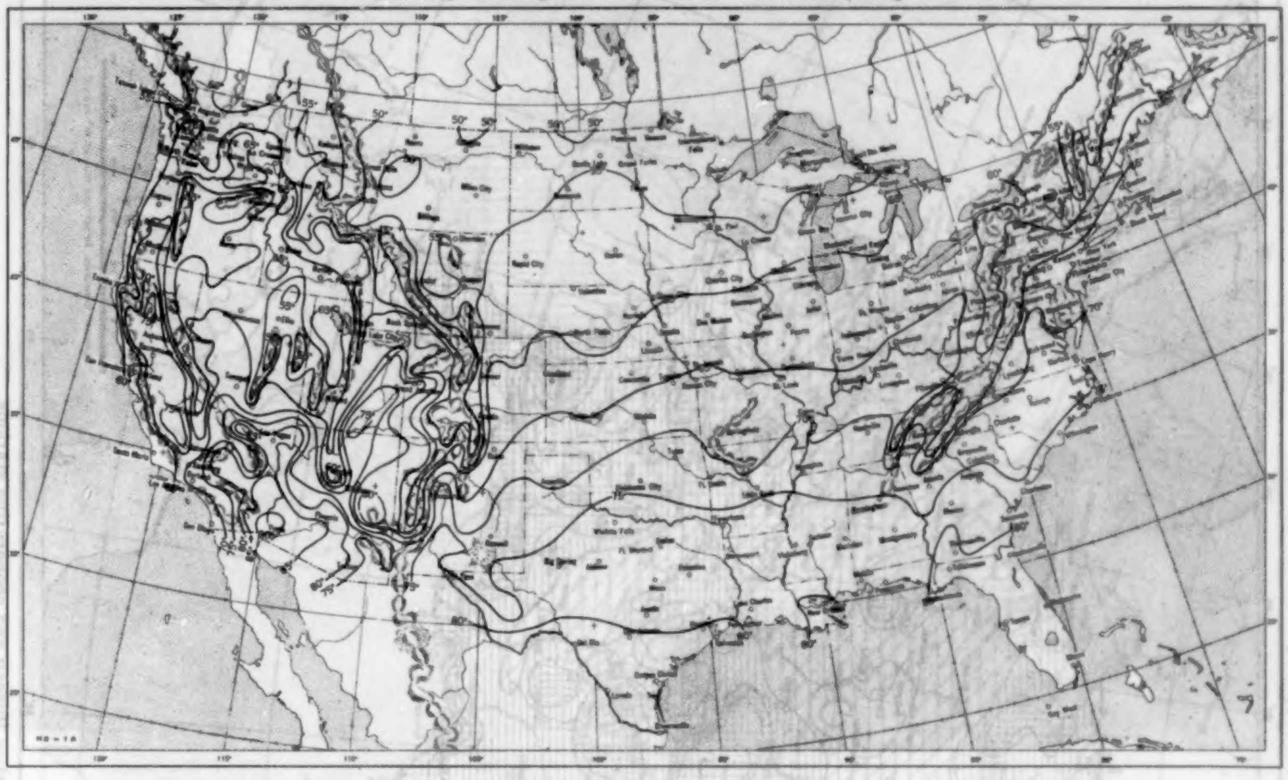
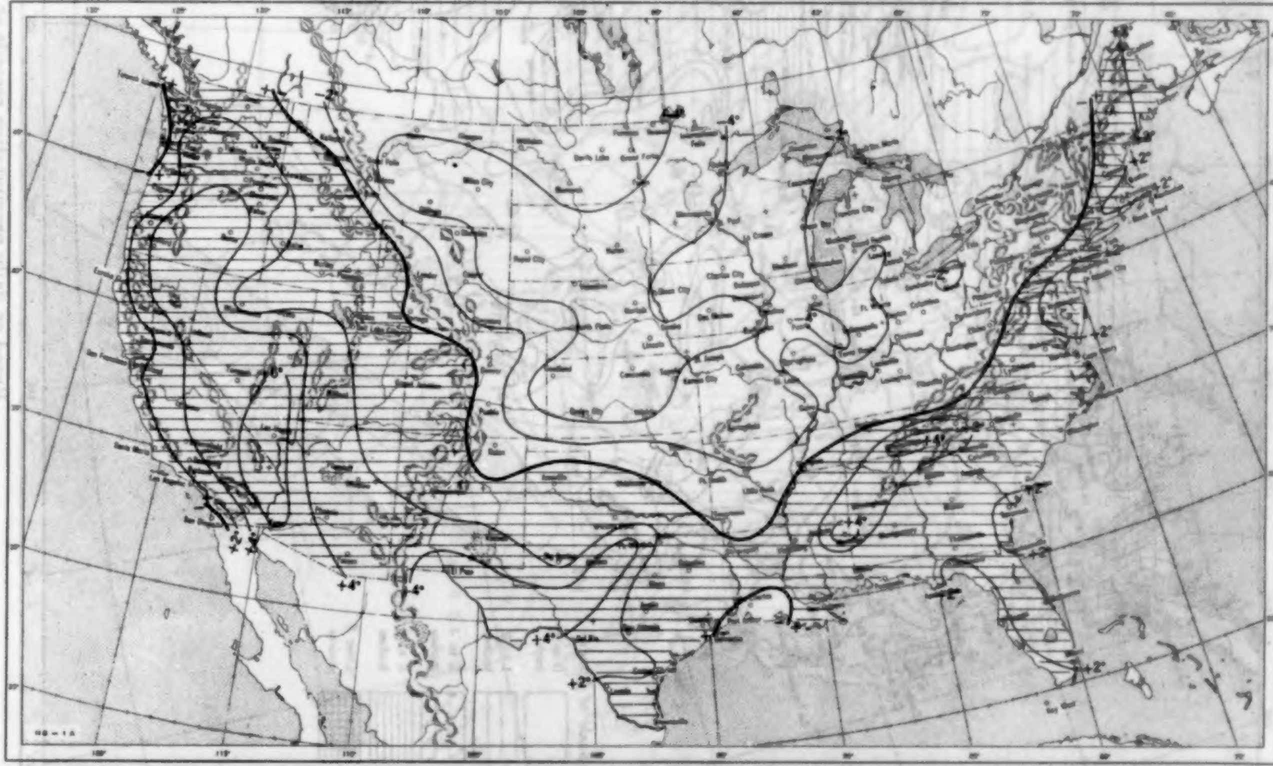
Chart I. A. Average Temperature (°F.) at Surface, September 1951.

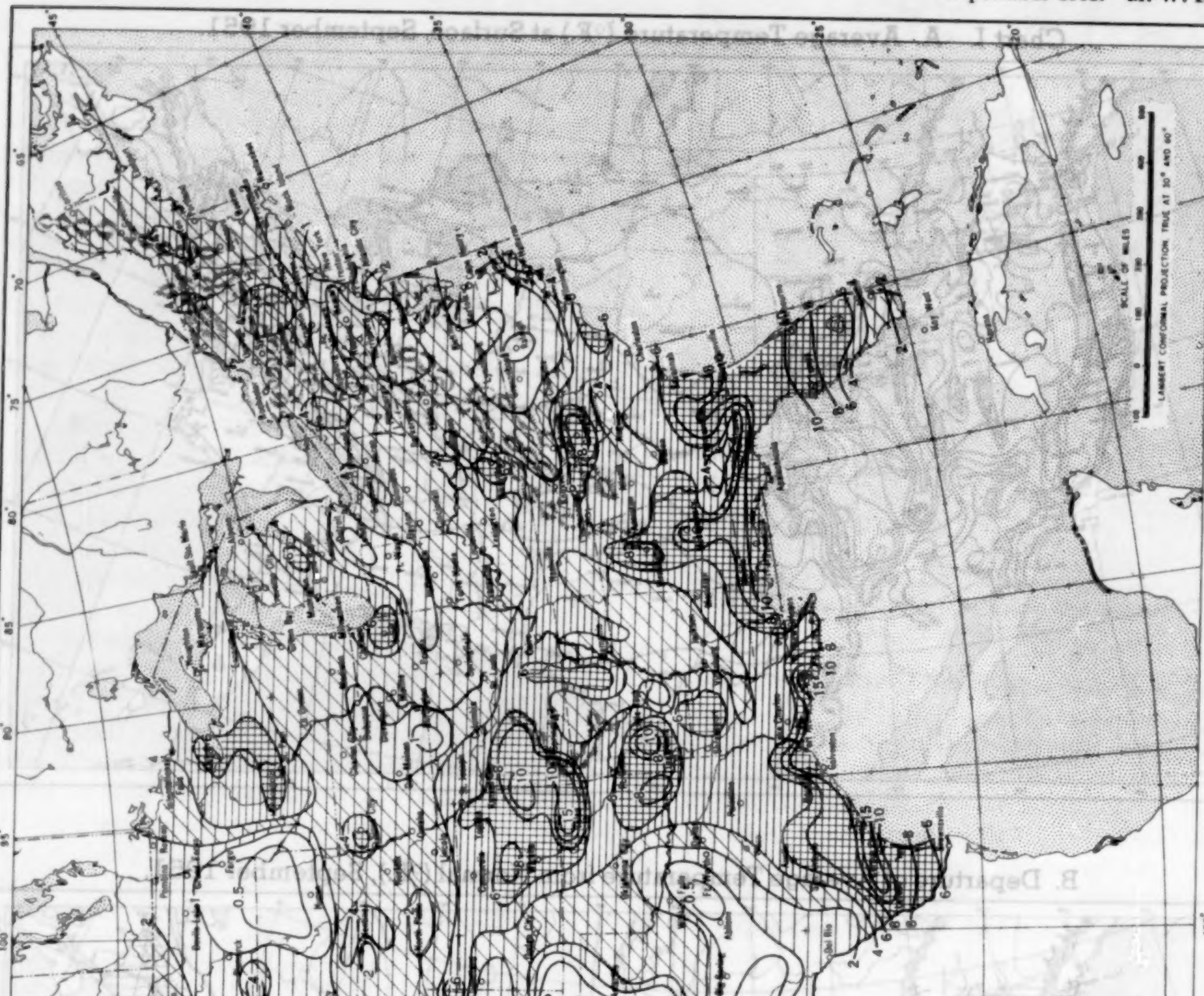


B. Departure of Average Temperature from Normal (°F.), September 1951.



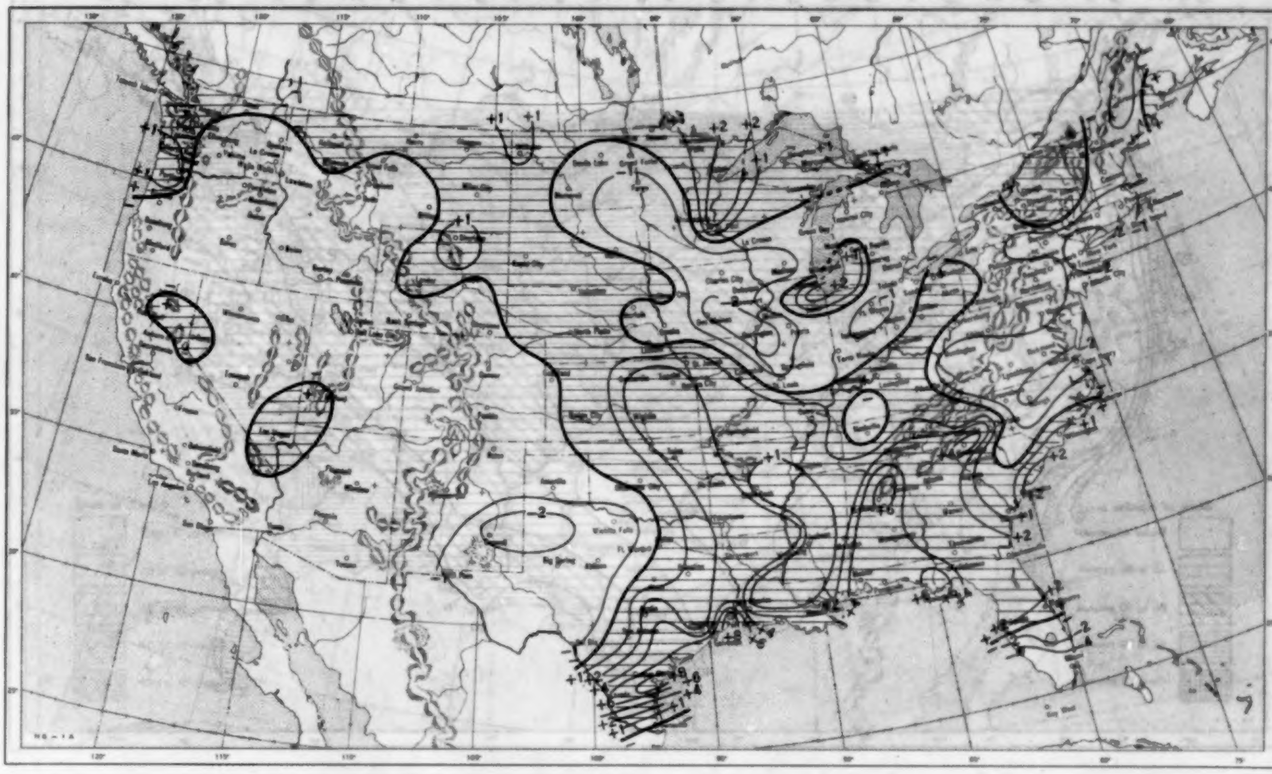
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), September 1951.



Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

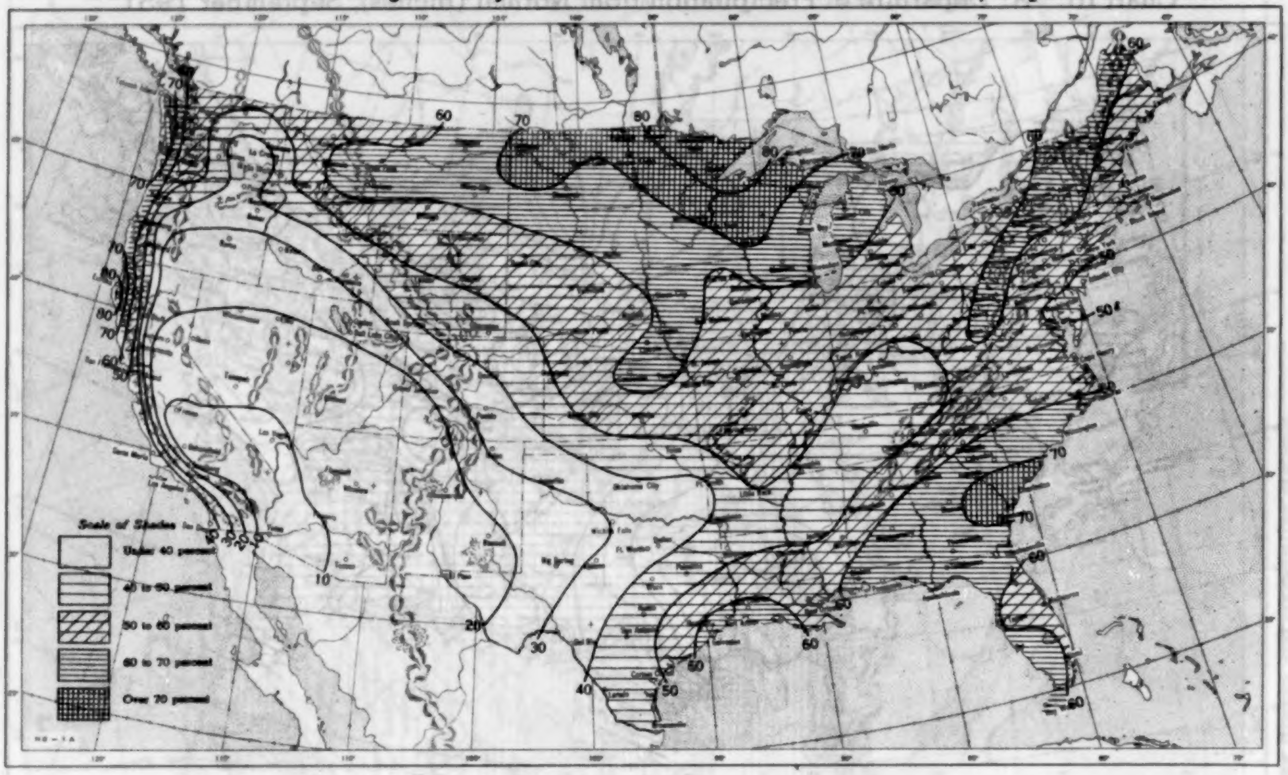
Chart III. A. Departure of Precipitation from Normal (Inches), September 1951.



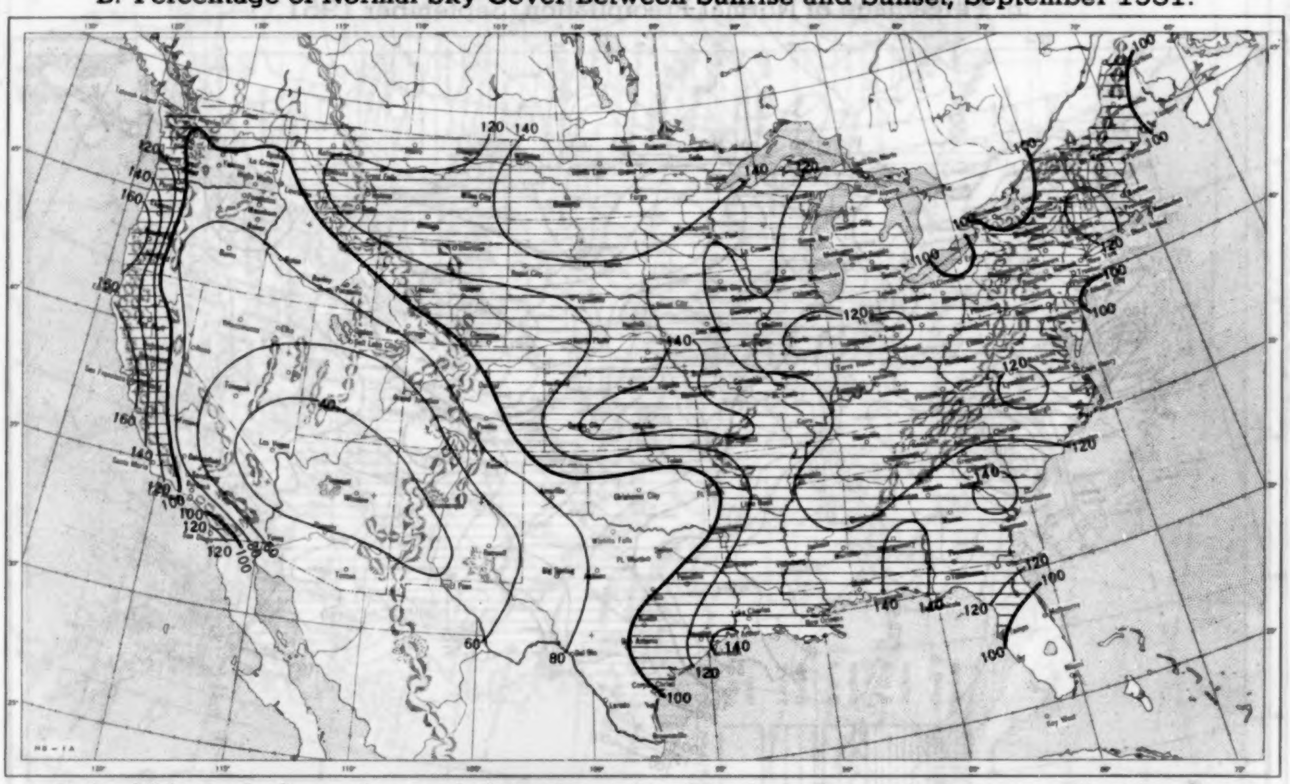
B. Percentage of Normal Precipitation, September 1951.

Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, September 1951.

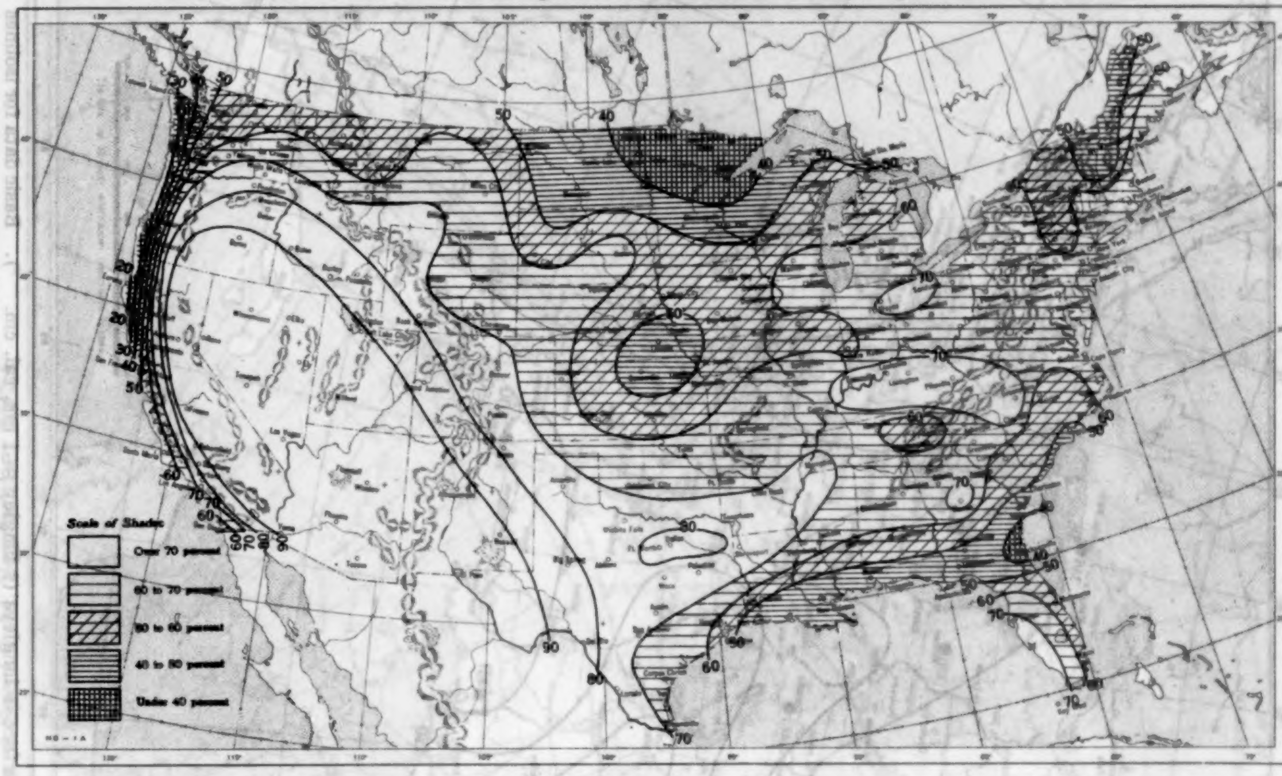


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, September 1951.

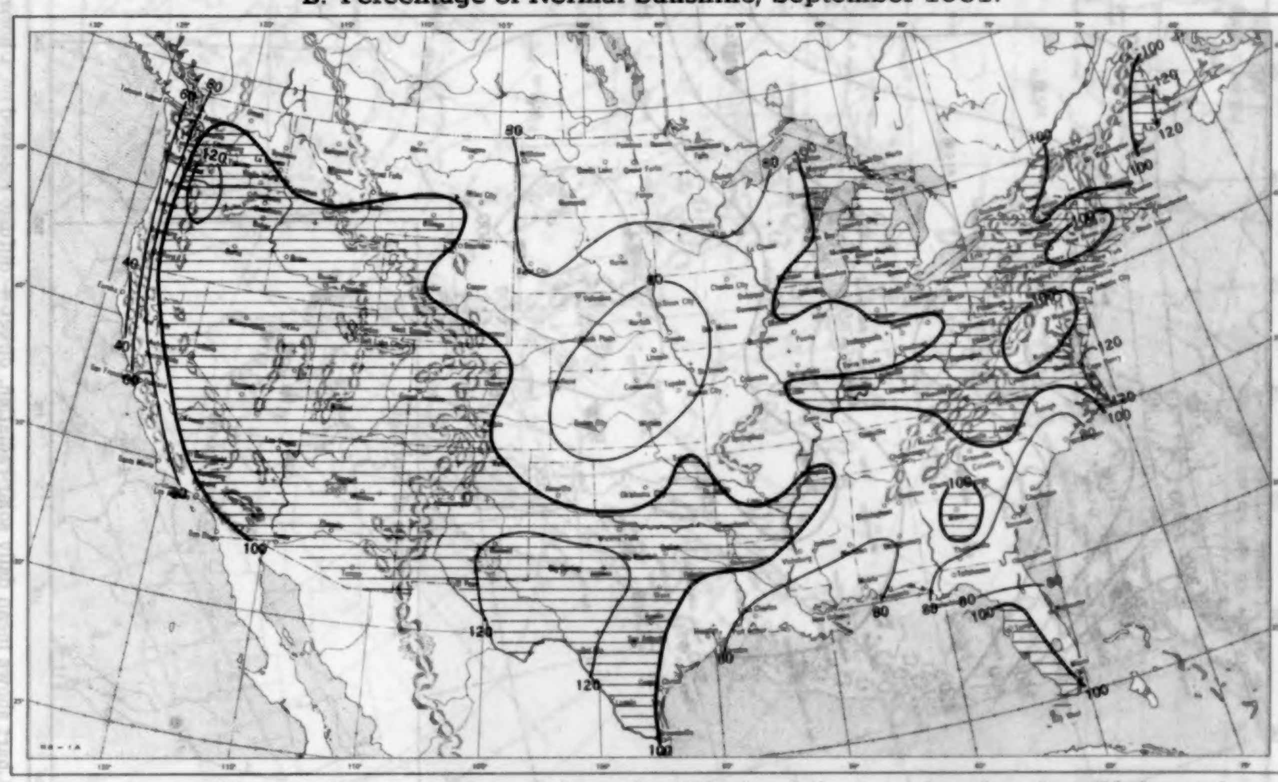


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, September 1951.



B. Percentage of Normal Sunshine, September 1951.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, September 1951. Inset: Percentage of Normal Average Daily Solar Radiation, September 1951.

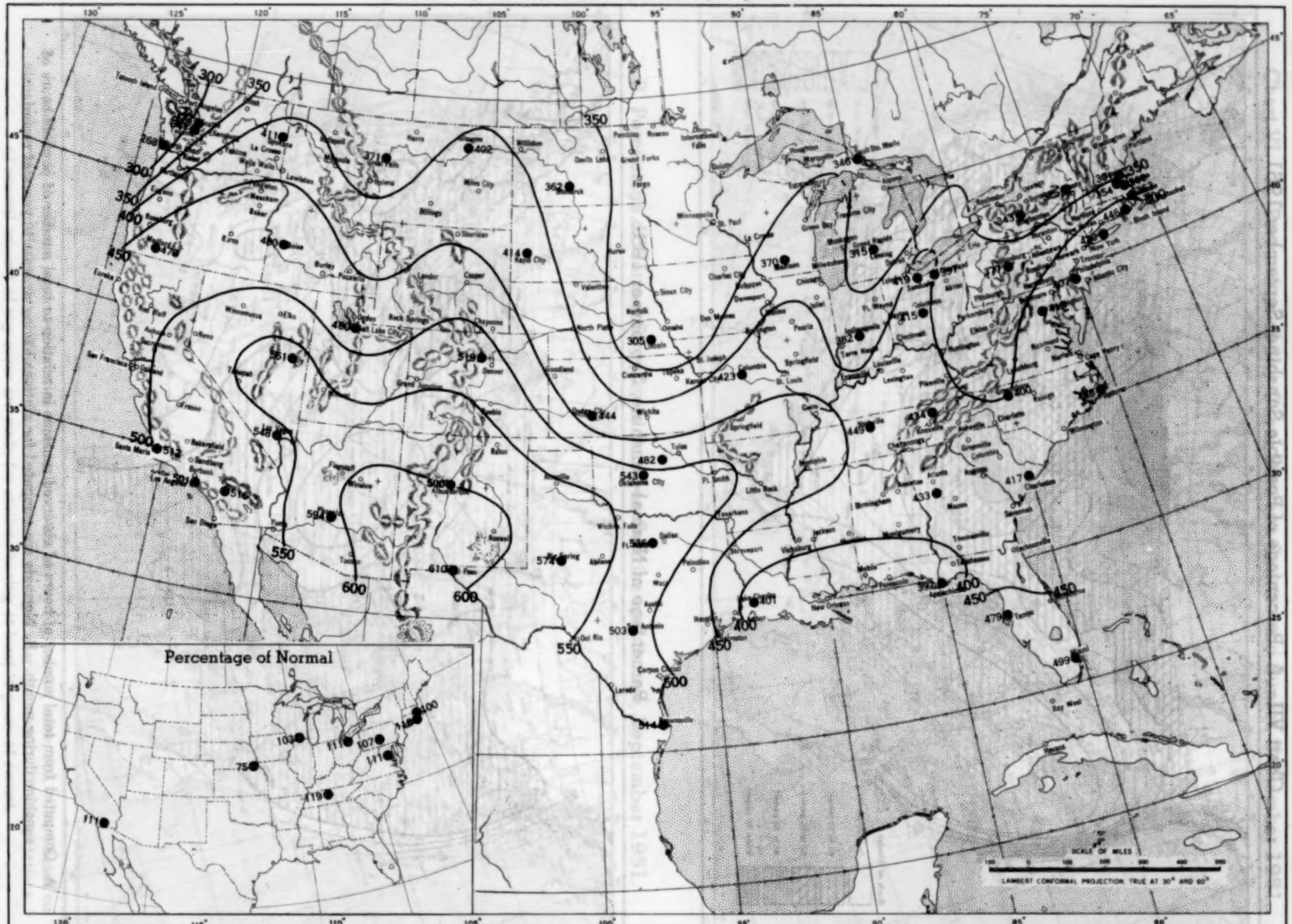
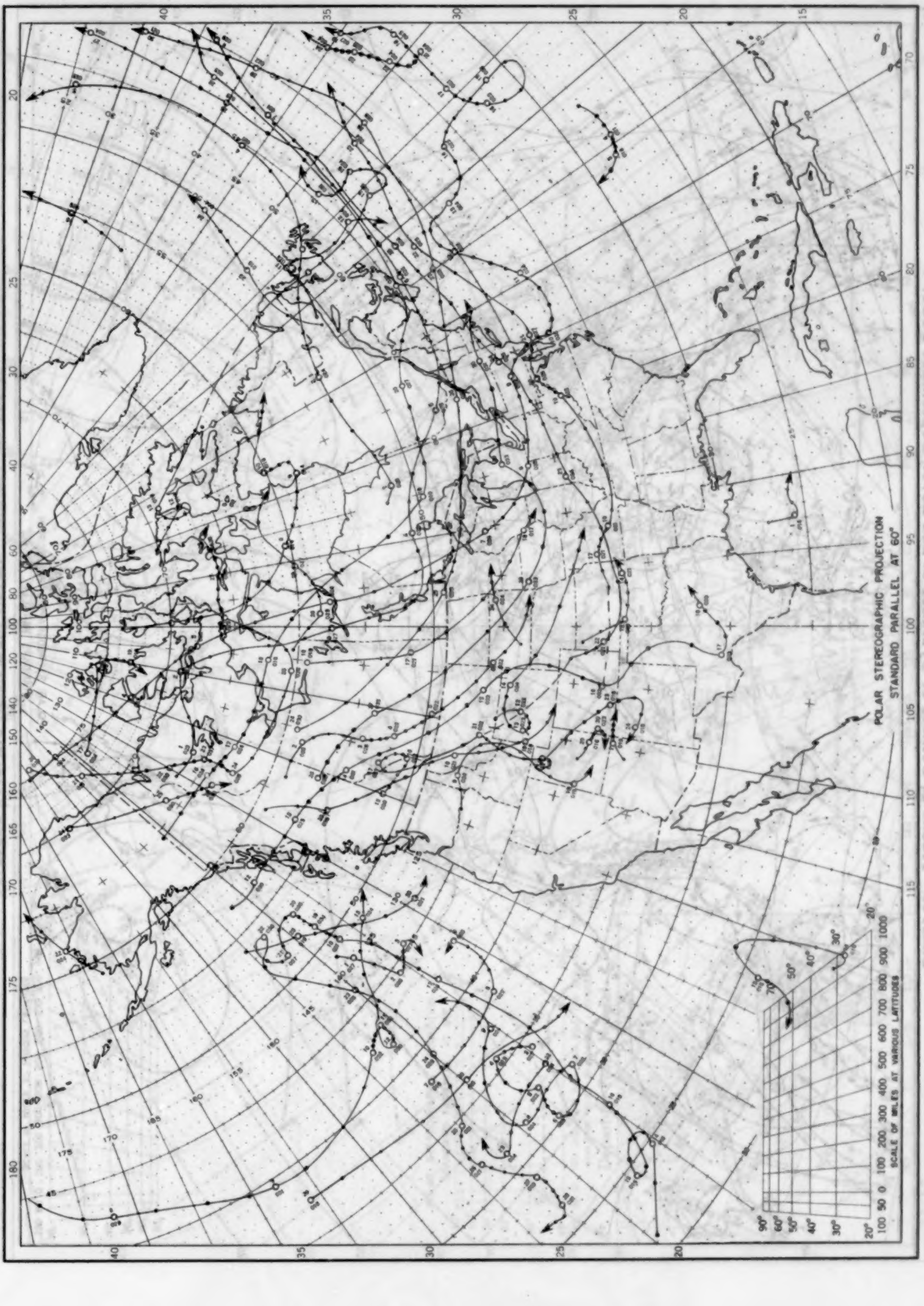


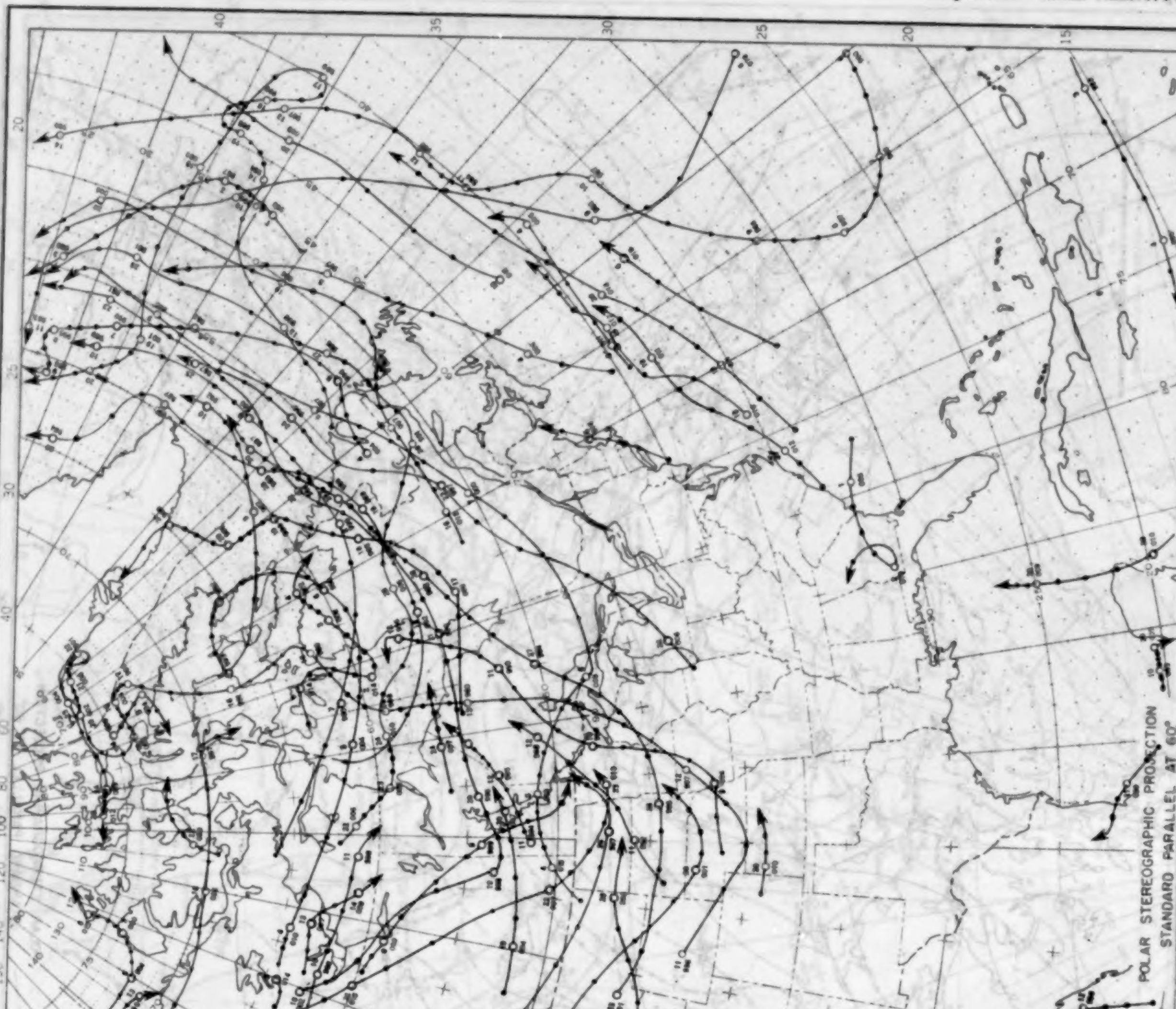
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, September 1951



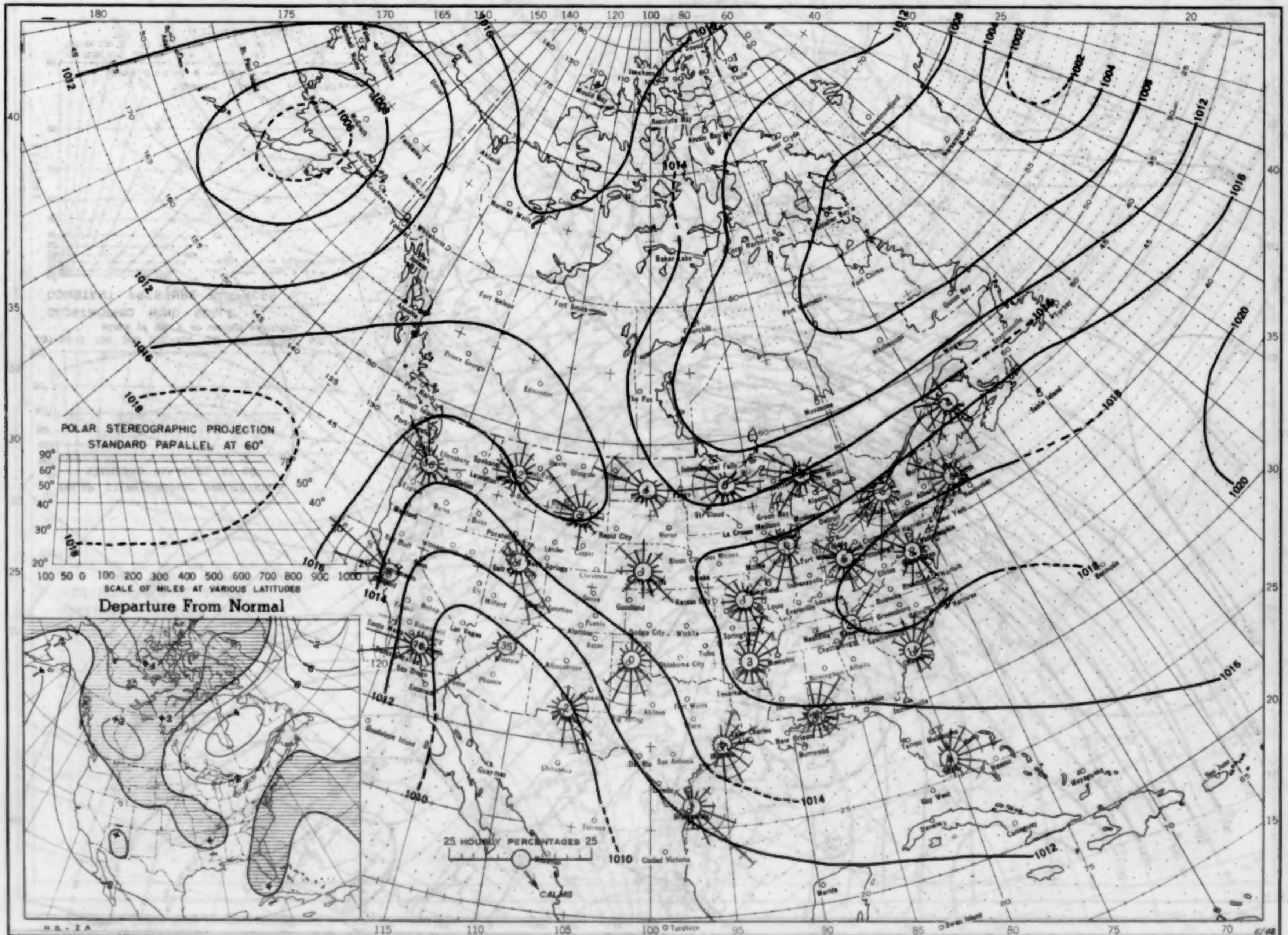
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, September 1951.



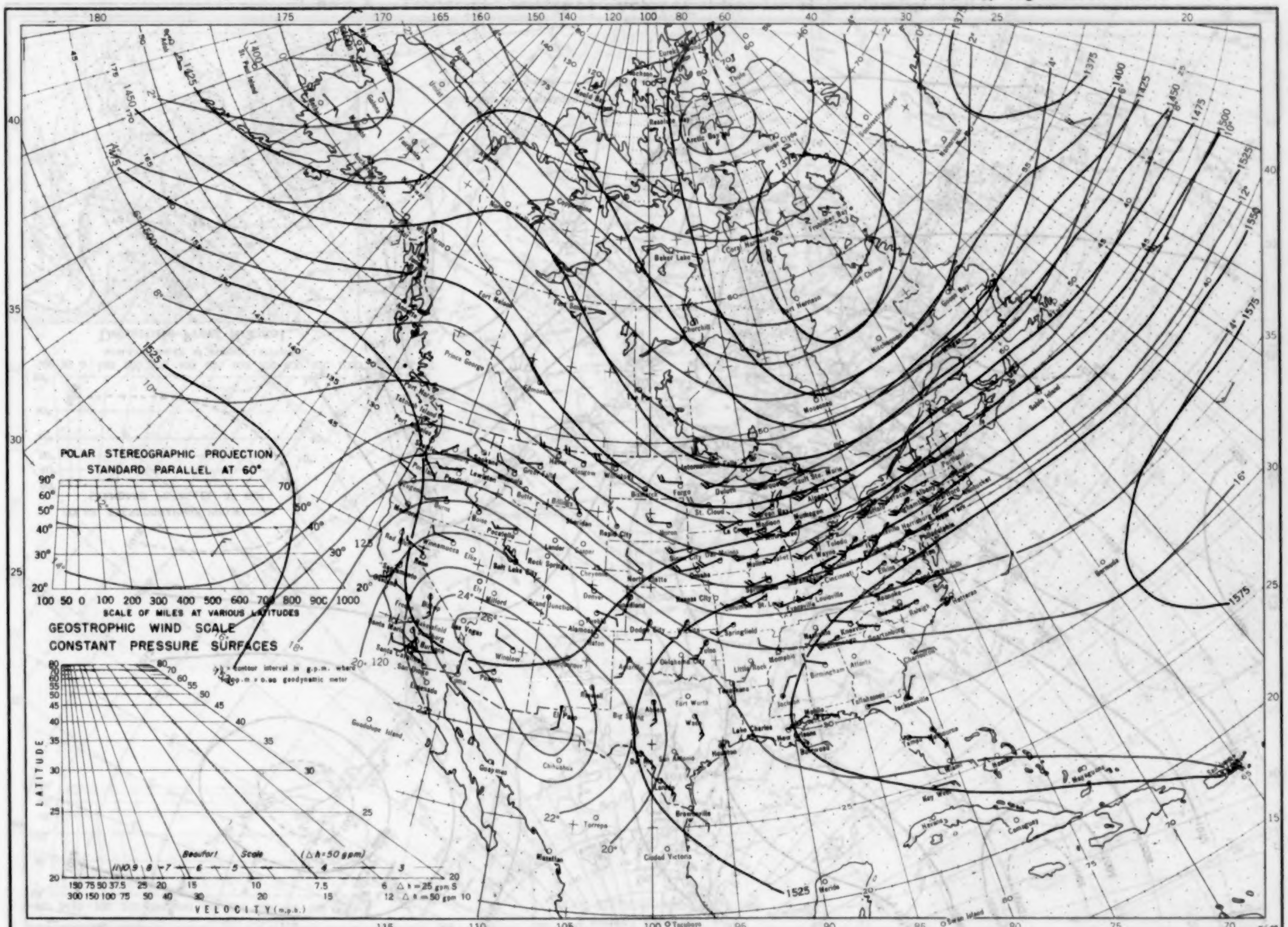
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, September 1951. Inset: Departure of Average Pressure (mb.) from Normal, September 1951.



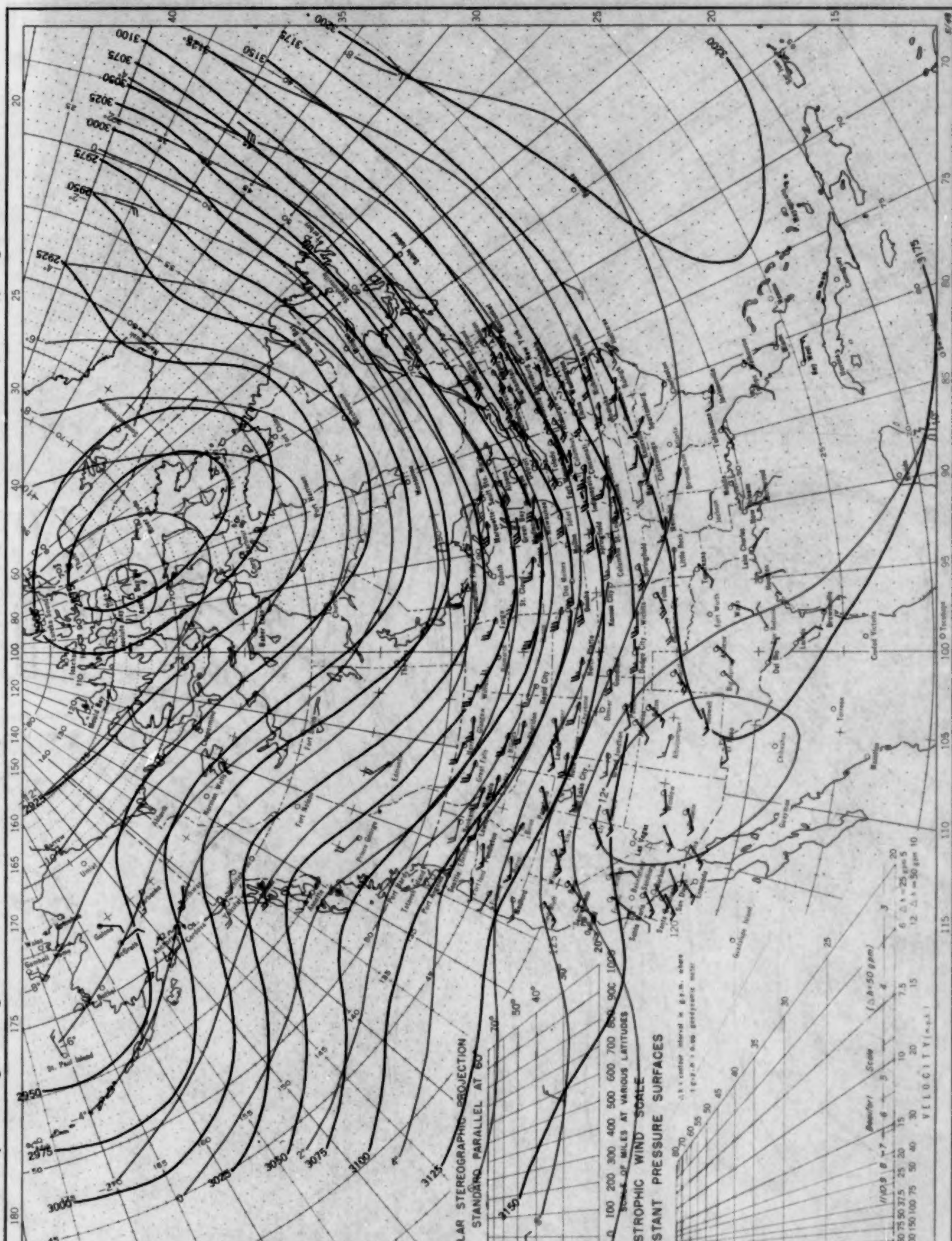
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid from map readings for 20 years of the Historical Weather Maps, 1899–1939.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), September 1951.



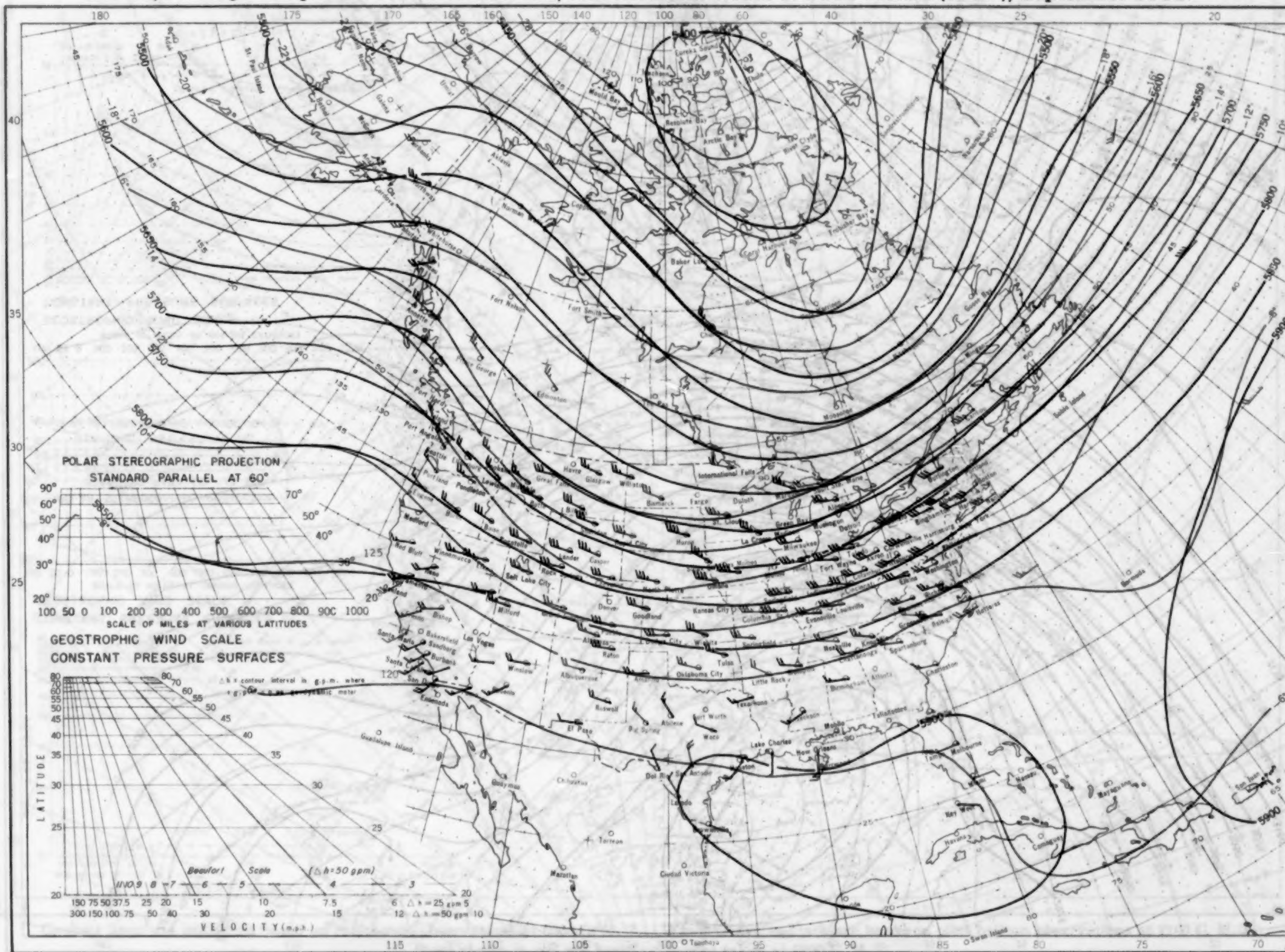
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), September 1951.



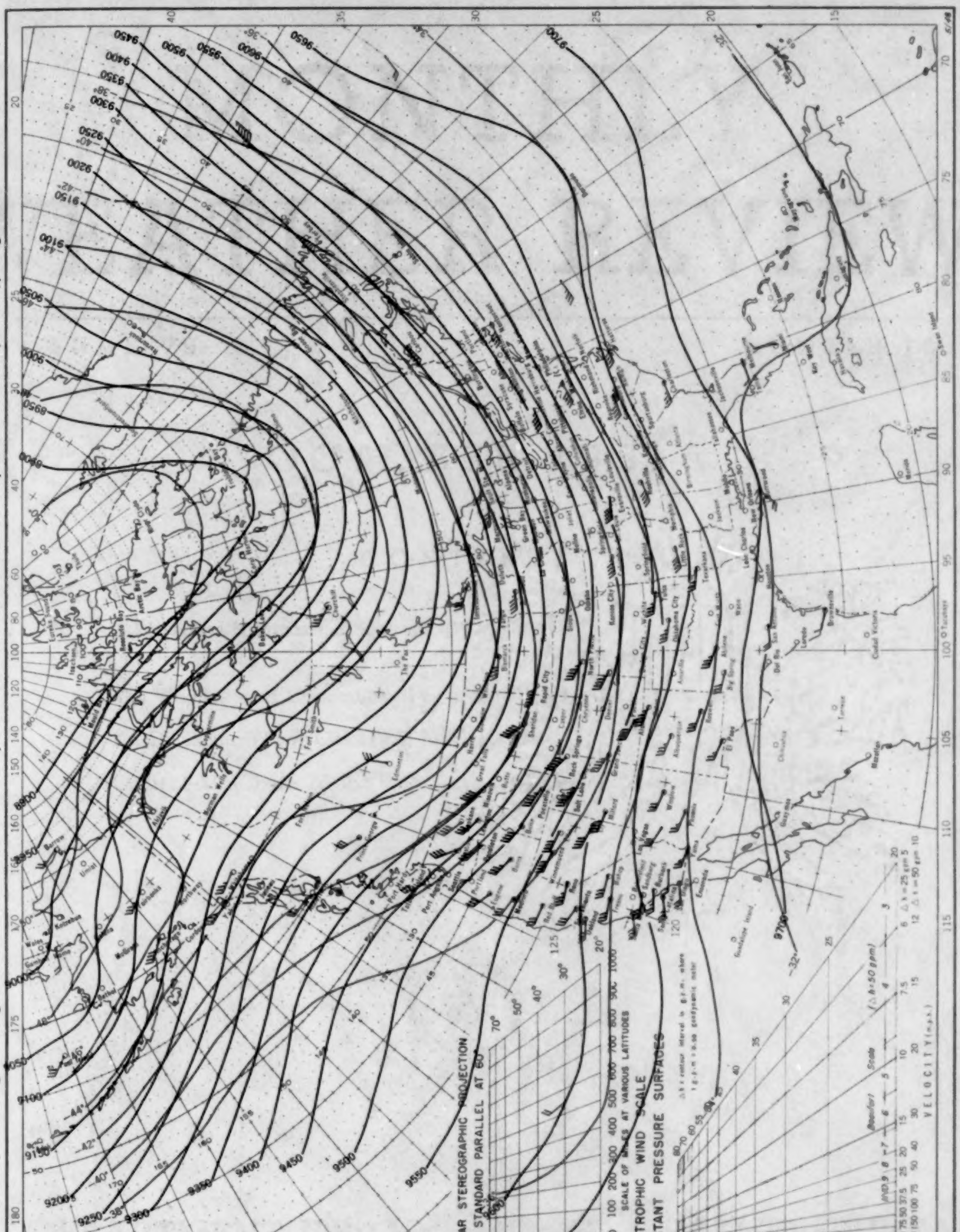
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), September 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), September 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.